A TECHNICAL REPORT

ON

DESIGN AND DEVELOPMENT OF AUXILIARY COMPONENTS FOR A NEW TWO-STROKE, STRATIFIED-CHARGE, LEAN-BURN GASOLINE ENGINE

BY

PROF. Ir. Dr. ALIAS BIN MOHD NOOR
AUTOMOTIVE DEVELOPMENT CENTRE (ADC)
FACULTY OF MECHANICAL ENGINEERING
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ABSTRACT

A unique stepped-piston engine was developed by a group of research engineers at *Universiti Teknologi Malaysia* (UTM), from 2003 to 2005. The development work undertaken by them engulfs design, prototyping and evaluation over a predetermined period of time which was iterative and challenging in nature. The main objective of the program is to demonstrate local R&D capabilities on small engine work that is able to produce mobile powerhouse of comparable output, having low-fuel consumption and acceptable emission than its crankcase counterpart of similar displacement. A two-stroke engine work was selected as it posses a number of technological challenges, increase in its thermal efficiency, which upon successful undertakings will be useful in assisting the group in future powertrain undertakings in UTM. In its carbureted version, the single-cylinder air-cooled engine incorporates a three-port transfer system and a dedicated crankcase breather. These features will enable the prototype to have high induction efficiency and to behave very much a two-stroke engine but equipped with a four-stroke crankcase lubrication system. After a series of analytical work the engine was subjected to a series of laboratory trials. It was also tested on a small watercraft platform with promising indication of its flexibility of use as a prime mover in mobile platform. In an effort to further enhance its technology features, the researchers have also embarked on the development of an add-on auxiliary system. The system comprises of an engine control unit (ECU), a direct-injector unit, a dedicated lubricant dispenser unit and an embedded common rail fuel unit. This support system was incorporated onto the engine to demonstrate the finer points of environmental-friendly and fuel economy features. The outcome of this complete package is described in the report, covering the methodology and the final characteristics of the mobile power plant.

ABSTRAK

Sebuah enjin unik yang di kenali sebagai enjin omboh-bertingkat, telah di bangunkan oleh sepasukan jurutera penyelidik dari Universiti Teknologi Malaysia (UTM), dari 2003 sehingga 2005. Usaha-usaha pembangunan ini meliputi aktiviti rekabentuk, penghasilan prototaip dan penilaian bagi satu jangka masa yang melihatkan aktiviti-aktiviti ini berulang-ulang dengan penuh cabaran, Objektif utama program adalah bagi mempamerkan kebolehan penyelidikan dan pembangunan tempatan di dalam penghasilan enjin kecil yang dapat menghasilkan kuasa keluaran yang setanding, mempamirkan penjimatan bahanapi, serta tahap pencemaran yang rendah jika di bandingkan dengan enjin dari jenis aruhan kotak engkol yang mempunyai anjakan yang sama. Kerja-kerja penghasilan enjin dua-lejang ini di pilih kerana ia memberi cabaran teknologi yang banyak dan boleh di atasi, serta dapat meningkatkan lagi kecekapan termalnya. Jika usaha-usaha ini berjaya ia dapat meningkatkan aktiviti pembangunan enjin kecil di masa hadapan di UTM. Dalam versi karburetor, enjin dua-lejang ini di pasang dengan sistem aruhan tiga-alur dan sistem penafasan kotak engkol. Ciri-ciri ini membolehkan ia bertindak sebagai enjin petrol dua-lejang tulin tetapi mempunyai sistem pelinciran seperti enjin jempat-lejang. Selepas melalui peringkat analisis ia melalui siri pengujian di peringkat makmal secar intensif. Ia juga di uji di dalam sebuah kenderaan yang bergerak (di permukaan air) dengan hasil yang memberangsangkan. Di dalam usaha seterusnya bagi meningkatkan prestasi enjin, para penyelidik juga turut membangunkan sebuah sistem sokongan. Sistem ini terdiri dari unit kawalan enjin, unit suntikan-terus bahanapi, unit penyembur minyak pelincir dan unit simpanan bahanapi pengongsian umum. Sistem sokongan ini bertujuan meningkatkan lagi aspek mesra-alam dan penjimatan bahanapi. Hasil dari usaha-usaha pembangunan ini di muatkan dalam lapuran ini yang juga meliputi methodologi serta menerangkan prestasinya sebagai sebuah penggerak-utama kecil mudah-alih.

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Chapter 1

INTRODUCTION

1.1 Objective

The objective of this research and development project is to develop auxiliary components for a new design of single-cylinder two-stroke air-cooled engine (output of not more than 15 kW). This engine will eventually incorporates features for performance excellence from the perspective of high power output, fuel economy, durability and low emission for applications in the non-automotive sectors.

1.2 Project Background

The current two-stroke engine designs are inefficient and impart environmental implications to human and plants in urban and non-urban areas where they operate. In Asian cities, they constitute the bulk of the engines for use in motorcycles and three-wheelers. With the hazardous nature of the pollutants emitted by the vehicles they are banned in Taipei, while in Bangkok the authority is seriously considering doing the same. The somewhat low combustion efficiency of today's two-stroke engine design can be improved through various means, making it possible for it to compliment the four-stroke version. The latter is a more complicated engine configuration having lesser power-to-weight ratio characteristic. During the last decade, there have been many versions of the two-stroke engines produced. A few have found commercial ventures while many are still at the prototype level or even on the drawing board.

Two-stroke petrol engines can be applied to a wide range of platforms ranging from the marine, inland (off-highway) and small aerial vehicles. In Malaysia the two-stroke engines are virtually imported. Some of the brands are *Yanmar* and *Kubota* (Japan), *Tatung* (Taiwan), *Lombardini* (Italy), *Robbin* and *Perkin* (United Kingdom) and *Briggs & Stratton* (US). All have been making in-roads for more than 40 years catering to the needs of builders, farmers and numerous utility users. They ranged in prices from as little as RM 900.00 to RM 5,000.00 depending on the quality, configuration, capacity and application. For a period between January 1999 to December 2000 Malaysia imported RM55.94 billions of machinery, appliance and parts [1]. The two-stroke engines (small engines) fall under this category.

The simplistic nature of the design, with relatively simple machining processes (than the four-stroke version), will provide improved power-to-weight ratio characteristic and lower production cost. Development of improved two-stroke engines must address piston scuffing, ring wear, oil consumption, starting, idling and scavenging problems. It also calls for the comprehensive investigations of the dynamic structural behaviour and improvement in the noise encapsulation techniques. Where engine cost, fuel efficiency or exhaust emissions are stressed, the development of new fuelling system is envisaged. The potential of retrofitting the new system will help to improve fuel consumption and exhaust emissions. To offset the addition of more components the use of aluminium die-casting and plastic mouldings (to minimise part count and assembly time) techniques are anticipated, making the mobile powerhouse extremely compact and light. The future of two-stroke engines with scavenging ports will essentially be determined by the development of new lubrication system, especially for high-speed operation. In all applications of small two-stroke engines, emission constraints have been implemented at the minimum level. To increase the performance of this version, the development of low-cost, miniaturise air-assisted fuel spray engine system is critical. In addition, the technology breakthrough in engine management technology will make the two-stroke configuration much more efficient and environment-friendly, leading the way for their application becoming more robust and widespread.

There is a revival of interest in the two-stroke engine technology worldwide. *Orbital Engine Corporation Ltd* of Australia reported that their new two-stroke engines could be manufactured at up to 30% lower (per unit cost) in relation to the four-stroke version [2]. It has 40% fewer parts, 35% lighter and obviously more compact.

New innovations will be the theme for the project as a whole. But more importantly the quest for technological capabilities will be the main focus. It is hope that the know-how will ultimately be transferred to local small- and medium-scale industries (SMIs) to reap the benefit of the locally developed technology for the eventual production and commercialisation of the final product.

1.3 Project Methodology

The approach in the implementation of the project will be as follows:

- **Design –** concept, analysis, Thermodynamics and engine simulation, working drawings, component development, manufacturing drawings (CAD/CAE) etc.

- **Prototyping -** material procurements, consumables, fabrication and assembly, component integrity analysis, electronics and control system, fuelling system, air-intake system, calibration and measurements, fuelling kit development, transmission configurations, cabling etc.

- **Laboratory Trials -** rig development (for combustion and optical access investigation), engine mapping (engine management system development) lubrication system investigation, ignition system optimisation, overall performance test (fuel consumption, acceleration and deceleration profiles), endurance test, emission test, overall system optimisation and synchronisation tests, tuning of the exhaust and intake, consultations and expert advice

- **Field Trials –** cyclic field trial investigation for durability and endurance (as described by *SAE* procedures), fuel consumption monitoring, instrumentation and data recordings**,** consumable**,** consultation and expert advice

- **Refinement** – fine tuning of the complete system (control strategies etc.)

1.4 Duration

The estimated duration of the implementation of the project was for three (3) years beginning in May 2002 till April 2005. Due to some technical glitches the project was extended till to end of July 2005.

1.5 Market Analysis

Malaysia import large volume of small engines (RM1000 to RM 5000) into the country with applications being in the agriculture, industry and construction sector. Small two-stroke engine applications in the future are numerous ranging from the construction industry (e.g. mini excavator, vibrating roller and multi-function tractor) to compressor and machineries (e.g. generator, hydraulic power pack and high pressure washer) and possible substitution in the automotive and aerial applications. The potential markets of the future will be in Asia, China, Latin America and Eastern Europe where cost are a prime consideration [2].

Considering there are many divisions of the local manufacturing sector capable of producing engine components, the local production of small engine is of great possibility. This will translate into the reduction of foreign imports thus reducing the outflow of hard cash. In anticipation of the globalisation of trade, the opportunities for export will also be tremendous.

1.6 Business Analysis

The two-stroke engine production in Malaysia will open numerous opportunities especially for the growth of small- and medium-scale industries (SMI). The parts are relatively simple to produce making it easier for small- and medium scale industries (metal-based) to flourish and complement each other. Currently *Modenas* would be in a position to include the two-stroke engine production apart from the four-stroke, which is the mainstay of the establishment at the moment. To the lesser extend companies such as *Boon Siew, Tan Chong* and the *Lion* group would also benefit in the two-stroke small engine production not only for the local market but also the growing ASEAN market in view of *AFTA* coming into force in 2003.

The future of the two-stroke engine in general, and particularly that of the two-stroke diesel engine beyond the non-transport sector (especially for passenger cars) will depend upon how far a successful combination of scavenging, charging, combustion technology improvement can be made without jeopardising its classical advantages in terms of power-to-weight ratio and efficiency. It is hopeful that the two-stroke version will add to the range of family of Malaysian-made engines pioneered *Petronas* (EO1 engines family) and *Proton* small engine family *(SEng)*.

Chapter 2

TECHNOLOGY OVERVIEWS AND CHALLENGES

2.1 Historical Background of Two-stroke Engines

It is generally accepted that the two-stroke cycle engine was invented by Sir Dugald Clerk in England at the end of the 19th Century. It is a form of engine using crankcase compression for the induction process, including the control of the timing and area of the exhaust, transfer and intake ports by the piston. The design was patented by Joseph Day in England in 1891. His engine was the original "three-port" engine and is the forerunner of the simple two-stroke engine which has been has in common usage since that time.

Some of the early applications were in motorcycle and are well recorded by Caunter [3]. The first engines were produced by Edward Butler in 1887 and by J.D. Roots, in the form of the Day crankcase compression type, in 1892; both of these designs were for powered tricycles. Considerable experimentation and development was conducted by Alfred Scott, and his Flying Squirrel machines competed very successfully in Tourist Trophy races in the first quarter of the 20th Century. They were designed quite beautifully in both the engineering and in the aesthetic sense. After that, two-stroke engines faded somewhat as competitive units in racing for some years until the supercharged DKW machines of the '30s temporarily revived their fortunes. With the banning of supercharging for motorcycle racing after the Second World War, the two-stroke engine lapsed again until 1959 when the MZ machines, with their tuned exhaust expansion chambers and disc valve induction systems, introduced a winning engine design which has basically lasted to the present day.

Today, two-stroke-engine for motorcycles, scooters and mopeds are still produced in very large numbers for general transport and for recreational purposes, although the legislative pressure on exhaust emissions in some countries has produced a swing to a four-stroke engine replacement in some cases. Whether the two-stroke engine will return as a mass production motorcycle engine will depend on the result of research and development being conducted by all of the manufacturers at the present time. There are some other applications with engines which are similar in design terms to those used for motorcycles, and the sports of go-kart and hydroplane racing would fall into this category.

The two-stroke engine is also used for lightweight power units which can be employed in various attitudes as handheld power tools. Such tools are chainsaws, brush cutters and concrete saws, to name but a few, and these are manufactured with a view to lightness and high specific power performance.

The earliest outboard motors were pioneered by Evinrude in the United States about 1909, with a 1.5 hp unit, and two-stroke engines have dominated this application until the present day. Some of the current machines are very sophisticated designs, such as 300hp V6- and V8-engined outboards with remarkably efficient engines considering that the basic simplicity of the two-stroke crankcase compression engine has been retained. Although the image of the outboard motor is that it is for sporting and recreational purposes, the facts are that the product is used just for as heavily for serious employment in commercial fishing and for everyday water transport in many parts of the world. The racing of outboard motors is a particularly exciting form of automotive sport,

Some of the new recreational products which have appeared in recent times are snowmobiles and water scooters, and the engine type almost always employed for such machines in the two-stroke engine. The use of this engine in a snowmobile is almost an ideal application, as the simple lubrication system of the two-stroke engine is perfectly suited for sub-zero temperature conditions. Although the snowmobile has been described as a recreational vehicle, it is actually a very practical means of everyday transport for many people in Arctic environment.

The use of the two-stroke engine in snowmobiles has had an interesting history, and some quite sophisticated machines were product in the 1960s, such as the Auto-Union vehicle from West Germany and the simpler Wartburg from East Germany. The Saab car from Sweden actually won the Monte Carlo Rally with Eric Carlson driving it. Until recent times, Suzuki built a small two-stroke-engined car in Japan. With increasing ecological emphasis on fuel consumption rate and exhaust emissions, the simple two-stroke-engined car disappeared, but interest in the design has seen a resurgence in resent times as the legislative pressure intensifies on exhaust acid emissions. Almost all car manufacturers are experimenting with various forms of two-stroke-engined vehicles equipped with direct fuel injection, or some variation of that concept in terms of stratified charging or combustion.

The use of the two-stroke engine in Compression Ignition (CI) or diesel form deserves special mention, even though it will not figure hugely in terms of specific design discussion within this book. The engine type has been use for trucks and locomotives, such as the designs from General Motors in America or Rootes-Tilling-Stevens in Britain. Both of these have been very successful in mass production. The engine type, producing a high specific power output, has also been a favourite for military installations in tanks and fast naval patrol boats. Some of the most remarkable aircraft engines ever built have been two-stroke engine diesel units, such as Junkers Jumo and the turbo-compounded Napier Nomad. There is no doubt that the most successful of all of the applications is that of the marine diesel main propulsion unit, referred to in my student days in Harland and Wolff's shipyard in Belfast as a "cathedral" engine. The complete engine is usually some 12m tall, so the description is rather apt. Such engines, the principal exponents of which were Burmeister and Wain in Copenhagen and Sulzer in Winterthur, were typically of 900mm bore and 1800mm stroke and ran at 60-100rpm, producing some 000 hp per cylinder. They had thermal efficiencies in excess of 50%, making them the most efficient prime movers ever made. These engines are very different from the rest of the two-stroke engine species in terms of scale but not in design concept.

The diesel engine, like its spark-ignition counterpart, is also under legislative pressure to confirm to ever-tighter emissions standards. For the diesel engine, even though it provides very low emissions of carbon monoxide and of hydrocarbons, does emit visible smoke in the form of carbon particulates measurable levels of nitrogen oxides. The level of emission of both of these latter components is under increasing environmental scrutiny and the diesel engine must confirm to more stringent legislative standards by the year 2000. The combination of very low particulate and NOx emission is a tough R&D proposition for the designer of CI engines to be able to meet. As the combustion is lean of the stoichiometric mixture by some 50% at its richest setting to avoid excessive exhaust smoke, the exhaust gas is oxygen rich and so only a lean burn catalyst can be used on either a two-stroke or a four-stroke cycle engine. This does little, if anything at all, to reduce the nitrogen oxide emissions. Thus, the manufacturers are again turning to the two-stroke cycle diesel engine as a potential alternative powerplant for cars and trucks, as that cycle has inherently a significantly lower NOx emission characteristic. Much R&D is taking place in the last decade of the 20^{th} Century with a view to eventual manufacture, if the engine meets all relevant criteria on emissions, thermal efficiency and durability.

It is probably true to say that the two-stroke engine has produced the most diverse opinions on the part of both the users and the engineers. These opinions vary from fanatical enthusiasm to thinly veiled dislike. Whatever your view, at this early juncture in reading this book, on other engine type has ever fascinated the engineering world to quite the same extent. This is probably because the engine seems so deceptively simple to design, develop and manufacture. That the very opposite is the case may well be the reason that some spend a lifetime investigating this engineering curiosity. The potential rewards are great, for no other engine cycle has produced, in one constructional form or another, such high thermal efficiency or such low specific fuel consumption, such high specific power criteria referred to either swept volume, bulk or weight, nor such low acid exhaust emissions.

2.2 The fundamental method of operation of a simple two-stroke engine

An example of a simple two-stroke engine is shown in the Figure 2.1, with the various phrases of the filling and emptying of the cylinder illustrated in Figure 2.2 (a)-(d). The simplicity of the engine is obvious, and with all the processes controlled by the upper and lower edges of the piston.

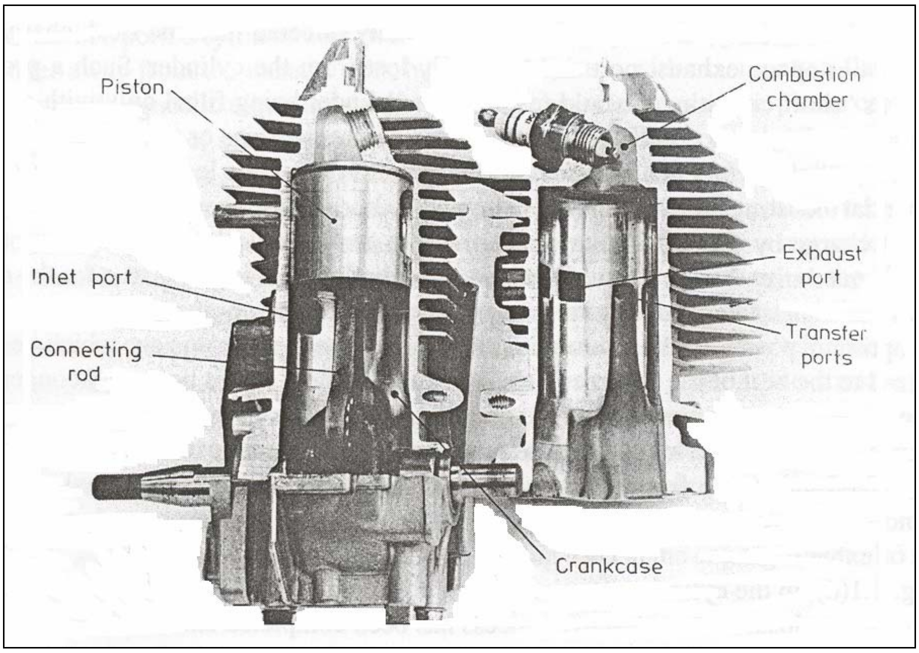


Figure 2.1: A simple two-stroke engine.

In Figure 2.2(a), the piston, the trapped air and fuel charge is being ignited by the spark plug, producing a rapid rise in pressure and temperature which will drive the piston down on the power stroke. Below the piston, the opened inlet port is inducing air from the atmosphere into the crankcase due to the increasing volume of the crankcase lowering the pressure below the atmospheric value. The crankcase is sealed around the crankshaft to ensure the maximum depression within it. To induce fuel into the engine, the various options exists of either placing a carburetor in the inlet tract, injecting fuel into the crankcase or transfer ducts, or injecting fuel directly into the cylinder before or after the closure of the exhaust port. Clearly, if it is desired to operate the engine as a diesel power unit, the latter is the only option, with the spark plug possibly being replaced by a glow plug as an initial starting aid and the fuel injector placed in the cylinder head area.

In Figure 2.2 (b), the piston, the exhaust port has been opened. It is often called the release point in the cycle, and this allows the transmission into the exhaust duct of a pulse of hot, high-pressure exhaust gas from the combustion process. As the area of the port is increasing with crankshaft angle, and the cylinder pressure is falling with time, it is clear that the exhaust duct pressure profile with time is one which increases to a maximum value and then decays. Such a flow process is described as unsteady gas flow and such a pulse can be reflected from all pipe area changes, or at the pipe end termination to the atmosphere. These reflections have a dramatic influence on the engine performance. Below the piston, compression of the fresh charge is taking place. The pressure and temperature achieved will be a function of the proportionate reduction of the crankcase volume, i.e., the crankcase compression ratio.

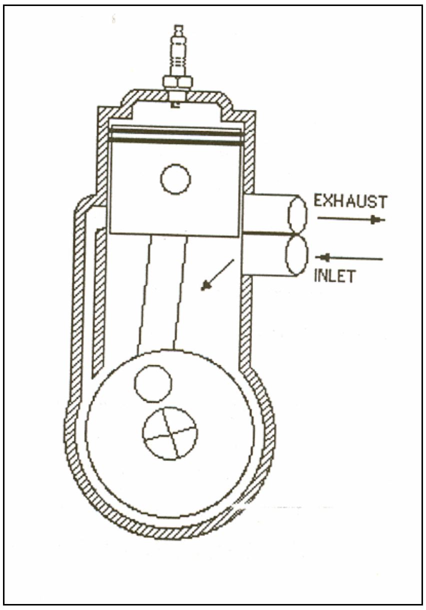


Figure 2.2 (a): Compression and induction

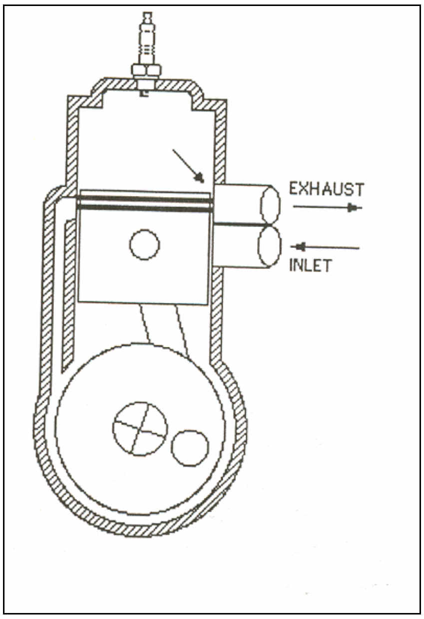


Figure 2.2 (b): Blow-down exhaust period

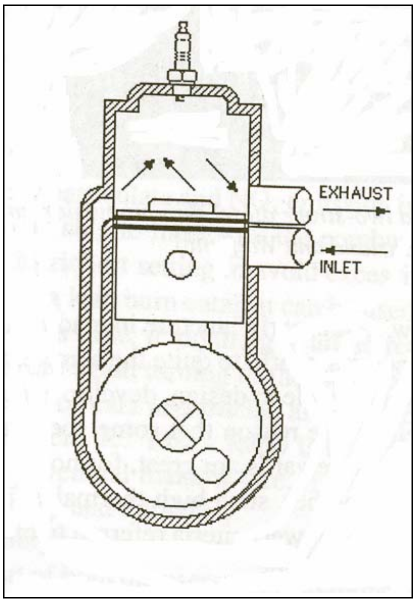


Figure 2.2 (c): Fresh charge transfer

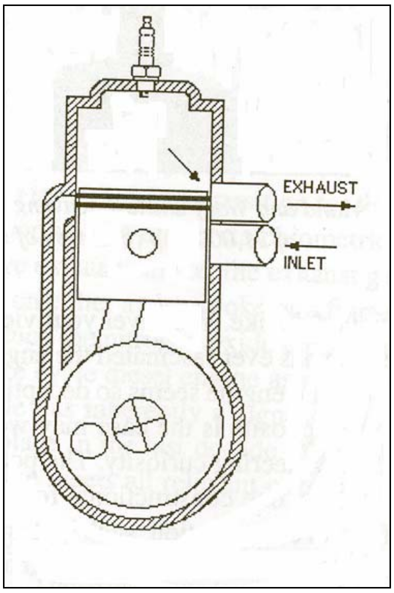


Figure 2.2 (d): Approaching exhaust closing

In Figure 2.2 (c), the piston, the exhaust process, also called “blow-down”, is nearing completion and, with the piston having uncovered the ports, this connects the cylinder directly to the crankcase through the transfer ducts. If the crankcase pressure exceeds the cylinder pressure then the fresh charge enters the cylinder in what is known as the scavenge process. Clearly, if the transfer ports are badly directed then the fresh charge can exit directly out of the exhaust port and be totally lost from the cylinder. Such a process, referred to as “short-circuiting,” would result in the cylinder being filled only with exhaust gas at the onset of the next combustion process, and no pressure rise or power output would ensue. Worse, all of the fuel in a carbureted configuration would be lost to the exhaust with a consequential monstrous emission rate of unburned hydrocarbons. Therefore, the directioning of the fresh charge by the transfer ports should be conducted in such a manner as to maximize the retention of it within the cylinder. This is just as true for the diesel engine where for the highest trapped air mass can be burned with an appropriate fuel quantity to attain the optimum power output. It is obvious that the scavenge process is one which needs to heavily on the scavenge process is one which needs to be optimized to the best of the designer’s ability. It should be clear that it is not possible to have such a process proceed perfectly, as some fresh charge will always find a way through the exhaust port. Equally, no scavenge process, however extensive or thorough, will ever leach out the last molecule of exhaust gas.

In Figure 2.2 (d), in the cylinder, the piston is approaching what is known as the “trapping” point, or exhaust closure. The scavenge process has been completed and the cylinder is now filled with a mix of air, fuel if a carbureted design, and exhaust gas. As the piston rises, the cylinder pressure should also rise, but the exhaust port is still open and, barring the intervention of some unsteady gas-dynamic effect generated in the exhaust pipe, the piston will spill fresh charge into the exhaust duct to the detriment of the resulting power output and fuel consumption. Should it be feasible to gas-dynamically plug the exhaust port during this trapping phase, then it is possible to greatly increase the performance characteristics of the engine. After the exhaust port is finally closed, the true compression process begins until the combustion process is commenced by ignition. Not surprisingly, therefore, the compression ratio of a two-stroke engine is characterized by the cylinder volume after exhaust port closure and is called the trapped compression ratio to distinguish it from the value commonly quoted for the four-stroke engine. That value is termed here as the geometric compression ratio and is based on the full swept volume.

In summary, the simple two-stroke engine is a double-acting device. Above the piston, the combustion and power processes take place, whereas below the piston in the crankcase, the fresh charge is induced and prepared for transfer to the upper cylinder.

2.3 Problem Background

The advantages of two-stroke engine over its four-stroke counterparts are higher power-to-weight ratio, less components, simpler construction, and lower cost. What makes two-stroke engine more interesting is the absence of a dedicated lubrication system. To lubricate the piston, the crankshaft, and any moving parts inside the engine, the gasoline is normally premixed with lubricant oil. Unlike four-stroke engine, hence there is no oil sump at the bottom of the crankcase. Naturally, two-stoke engine is more preferable for small mobile applications such as lawnmowers and chainsaws.

Two-stroke engine has fewer components than four-stroke engine typically because two-stroke engine uses no valves. The air and mixture flow in and out of the combustion chamber through several ports on the cylinder walls. The piston movement will cover and uncover the ports (at correct time) for maximum fluid exchange inside the combustion chamber. The process of emptying the cylinder of burned gases and replacing them with a fresh mixture (or air) is called scavenging [4].

During the scavenging process, the intake and exhaust ports (at certain duration) are both open at the same time and some of the fresh air-fuel charge is lost out the exhaust port. This loss of fresh fuel is called short-circuiting. The typical two-stroke engine fuel loses is 30%-40% during this scavenging process, with losses of up to 70% under idle conditions [4]. Short-circuiting of fresh air/fuel mixture is one of the most undesired effects of two-stroke engine as pointed out by Stone [5].

Two significant problems associated with short-circuiting are high fuel consumption, and high percentage of un-burnt hydrocarbons (UHC) released with exhaust emission. Although the two-stroke engine releases a relatively high percentage of UHC, it has inherently low level of nitrogen oxides (NOx) exhaust emission [5]. All major problems of two-stroke engine are summarized in a relation chart Figure 2.3.

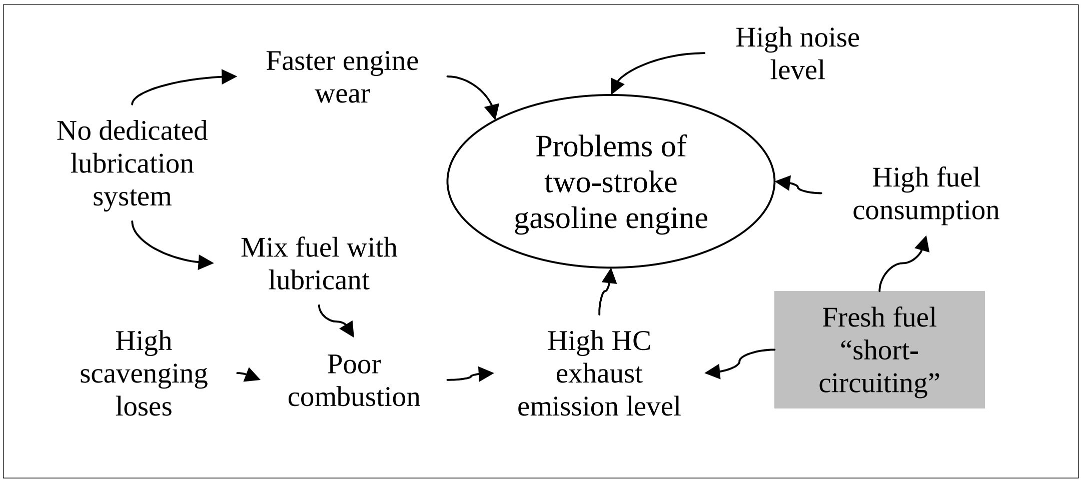


Figure 2.3: Problems of two-stroke engine in comparison with similar four-stroke counterparts [6].

With the ever increase of crude oil price, and more stringent emission level standard regulation throughout the continent, the two-stroke engine is facing greater challenge to remain competitive with its four-stroke counterparts. To counter such problem of two-stroke engine, the foremost measure is to minimize the problem of fresh fuel “short-circuiting” thus reducing part of exhaust emission level, and part of fuel consumption. Still under extensive development, a novel method of gasoline direct injection (GDI) is a known permanent solution to the fuel “short-circuiting” problem.

2.4 The Future of Two-Stroke Engines

The interim technologies that are now marketed to clean up two-strokes (*FICHT*, *Orbital*) are not clean enough to meet current California's off road CARB (California Air Regulatory Board) standards or expected future EPA (Environmental Protection Agency) off road standards. Even now, they are not very practical for engines that move rapidly up and down through the rpm range, like a typical bike engine. The "driveability" is just not there for motorcycle applications. There are expensive R&D solutions to fix direct injection, but the costs are very high to move to production (relative to the number of bikes you could sell) and require extensive electronic management and catalysts. A few street riders might pay the high price; I doubt an off-road rider is likely to accept the fancy electronics and hardware. Four-strokes are inherently cleaner and they have the potential to meet all future standards at a fraction of the cost of a "clean" two-stroke while delivering high output, excellent driveability and good fuel economy. There is extensive R&D going on by many OEMs which will keep prices down when products come to the market. So, while the mechanical simplicity of two-strokes is attractive, the cost to clean them up is high and the results are not promising.

The emissions standards tend to be a moving target, and are set as much on what can be done as on what is needed. So two strokes are always at a disadvantage, and it wouldn't surprise me to discover that the Big four (Honda, Kawasaki, Yamaha and Suzuki) are reluctant to tool up for volume production, only to have US and European standards revised below what they can accomplish.

Honda said that they did in fact have 'clean' two-stroke technology, but had concerns about putting a two-stroke street bike power-to-weight ratio in the hands of the general public. Basically, they could easily build a 136-160 kg bike with say 97 kW. Therefore they decided not to introduce the technology. But they have not did not rule out using the technology in the future.

From technical point of view, two strokes are not used more extensively is largely attributed to efficiency. By efficiency it is not the highway fuel consumption (although it's related) or brake power per litre, but rather brake thermal efficiency. In general two strokes have lower thermal efficiencies compared to four strokes for two main reasons: compression ratio and gas dynamics.

Firstly, the thermal efficiency of either a two- or four-stroke engine is a function of compression ratio. The nature of this relationship is complex, but efficiency is higher for a higher compression ratio. Putting it simply, a higher compression ratio causes higher pressures and temperatures in the cylinder and allows more mechanical work to be extracted for the cycle. Two-strokes tend to run lower compression ratios than four -strokes (this is due to porting and scavenging requirements) and broadly speaking have reduced efficiencies due to this alone. The pressurizing of the charge in a two stroke before it enters the combustion chamber raises the effective compression ratio (much like turbo charging), but this effect varies with engine speed and on the whole it's worse off than a four stroke.

The second reason two strokes have lower efficiency is due to gas dynamics. Gas flows are complex in a two-stroke in comparison to a four-stroke. Two strokes like to perform in certain rev ranges when scavenging is occurring in a favourable manner. This is usually referred to as being "on the pipe" or "in the power band". Here expansion waves are cleverly used to draw mixture through the crankcase and transfer ports and provide improved cylinder filling. Unfortunately, this only occurs in certain rev ranges depending on the pipe geometry and port timing and shape. Out of this favourable rev range the engine can suffer from inlet charge contamination by exhaust gases, or fresh charge being drawn unburned into the exhaust. The direct injection system will reduce or perhaps even eliminate the environmental side of the problem, but the gas flow problem will still exist. This will reduce combustion efficiency and hence brake thermal efficiency. The state of tune greatly affects this, but ultimately the control of gas flow will never be as good as a mildly tuned four stroke over the whole rev range.

But why are they used in some applications? The mechanical efficiency of a two-stroke is higher than a four-stroke since there is no valve gear mechanism. If the engine was designed to run at a set speed and a throttle setting it could perhaps come close (maybe even better) to the efficiency of a four stroke. This may be why they are used on outboards where revs and throttle are held constant for long periods of time. The other issues with outboards are weight, size and simplicity, areas where two strokes have a distinct advantage.

In Australia a trial was run on government fleet vehicles using direct-injection two-strokes using *Orbital*'s technology. It was hoped that they would return improved fuel economy over a conventional engine. This was not the case - fuel economy was worse. To the defence of the two-strokes it must be said that the cars may have been driven differently. Apparently the engines had more power than the originals and a power delivery that encouraged faster driving. The direct fuel-injection system produced by Orbital has found its ways in motorcycle application such as in the motorcycles of *Aprilia* where they are claiming awesome fuel mileage (36 km per litre) and low emissions (passes EURO2 standard).

Clean two-strokes are still not as clean as good four-strokes. Each time they get better, the four-strokes up the ante. Today's ULEV (Ultra Low Emission Vehicle) standards would have been considered impossible ten years ago, yet many cars already meet it. ULEV requires infinitesimal hydrocarbon, NO_X and CO emissions. It is now believe that an incredible two-stroke will have a hard time with that. Two-strokes require mixing fuel, or at the least, buying special oil for the oil injection system. Here a two-stroke that worked without mixed fuel would help quite a bit.

There is a lot of discussion in the industry around two- versus four-stroke engines in the small/recreational vehicle markets. As four-strokes are approaching two-stroke power density (when you include fuel and other system pieces to travel a certain distance), many manufactures are making guesses as to where the cost equation will fall out. Right now, two-stroke technology (specifically direct-injection) is expensive, and for the most part needs to be licensed, at significant cost, from suppliers (*Ficht* and *Orbital* are the best known examples). In markets that are very cost/price sensitive, and embrace the low technology solutions they can work on, acceptance of these new technologies are relatively slow to come about. Figure 2.4, 2.5 and 2.6 illustrate the currently leading technologies in fuel injection for small two-stroke engines by some renowned small engine developers.

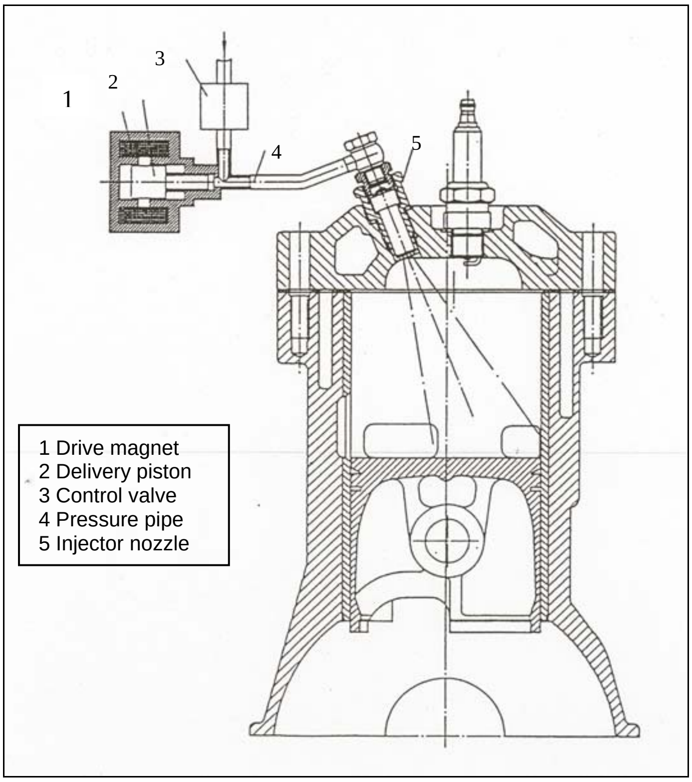


Figure 2.4: Principles of the FICHT-PDS Injection System [6]

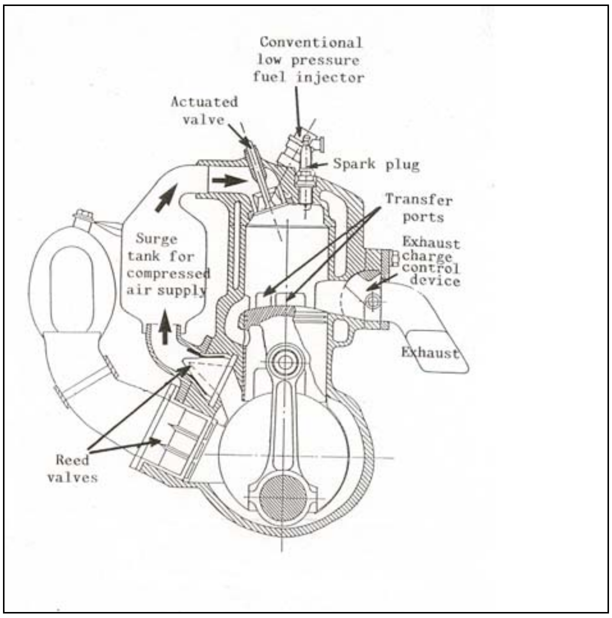


Figure 2.5: The use of direct-fuel injection system in a two-stroke engine [7]

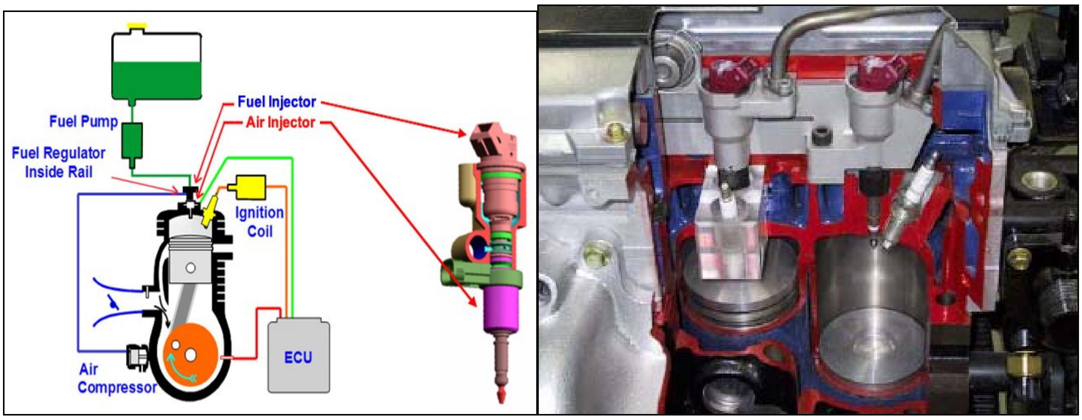


Figure 2.6: The *Orbital*'s direct fuel-injection system for small engines [8]

To move to fuel injection from carburetors is a huge change in the way a company must go about business. To make the jump to direct injection is an even greater change. For companies that have invested in the older technology solutions, there is a significant business risk in making the jumps. That is why you see new motorcycle companies coming out with fuel injection right away, while those who have carburetor solutions are slower to change. There are certainly will be big investments in both routes.

Beyond the cost of entry, the capability in many of the current advanced systems are somewhat lacking in the rider/user drivability perspective. This was highlighted in the V-Due experiment, and reviews on many of the motorcycle systems. Marine applications, where the throttle transients are minimal, application of this technology is reasonably straight forward and simple. Where there are large throttle transients, responding appropriately gets real difficult; both in the development of control strategies, and in calibrating them appropriately.

In the end, it comes down to a fairly complicated cost equation. To get a certain level of performance, what does it cost to develop and support the two-stroke engine technologies. With many of the racing endeavors changing to rules allowing four-strokes to compete in the traditional four-stroke arenas, the concept of needing to do two-strokes to keep the corporate name visible is going away.

Not all of the information to make a rational decision on the future of two-strokes is in yet, but it is coming fast. Trends point to four-stroke due to cost (to make and to maintain), customer satisfaction (less noise, no mixing of gas, less smell), and the current lack of availability of a good two-stroke technology alternative. In some applications, this is an easy change to four-stroke. In others it is not, and the manufacturers are busily looking for a 2-stroke saviour.

2.5 Future Applications of Two-stroke Engines

The two-stroke engine has been used in light aircraft, and today is most frequently employed in the recreational micro light machines. While the use in the automotive sector will be somewhat limited, there will be without doubt numerous other applications for this unique and versatile engine, such as small electricity generating sets, agriculture tiller and water pumps or engines for remotely piloted vehicles, i.e., aircraft for meteorological data gathering or military purposes. The applications are best described in Figure 2.7.


(a) (b)


(c) (d)

(e)

Figure 2.7: Current and future application of the two-stroke engines a) Motor cycle b) unmanned aerial vehicle c) mobile generator set d) recreational vehicle and e) three-wheeler transport

In summary the carbureted 2-stroke engines are a worldwide pandemic. There are over 50 million 2-stroke cycle engines in Asia alone, powering motorbikes, mopeds, “three-wheelers”, “auto-rickshaws”, “tuk-tuks”, and “tricycles”. These carbureted 2-stroke engines are characterized by high levels of hydrocarbon (HC), carbon monoxide (CO), and particulate matter (PM) emissions. Direct injection is a technology that has shown a great ability to reduce these emissions while at the same time improves fuel economy. Thus the fuel injector must accommodate both the full load fueling rate, as well as the minimum fueling rate required to idle the engine. A major difficulty with conventional fuel injection concepts for small two-stroke engines is the inability to provide precise well-atomized fuel sprays at these very small fuel deliveries, particularly as fuel consumption and emissions are reduced. Small two-stroke engines will still have a role especially for utility purposes.

Chapter 3

THE ENGINE CONCEPT AND ITS DESIGN

3.1 Introduction

Piston mass is naturally higher for a stepped piston design. However the unique approach means that for identical power cylinder bores the stepped piston is only around 20% heavier than a conventional looped scavenged two stroke piston. The multi section or step of the piston provides a flange stiffening effect resulting in thinner skirt sections. If necessary the mass increase can be reduced to under 15% by composite methods. However the engine uses the two stroke cycle and therefore with the absence of load reversals, piston mass is not as critical as it is for four stroke engines. The UTM developed stepped piston will also provides improved load bearing and guidance resulting in low ring wear and reduced piston noise.

The Stepped Piston Engine allows crankcase isolation to be achieved with a simple two-stroke engine design. This allows much greater durability and emissions potential with a high power density low mass engine. The engine design has long been used for powering unmanned, short range, observational aircraft for the defense sector and a prototype engine based on the stepped piston design has also been adapted for use in a fire pump.

Many design incorporating stepped-pistons were proposed in the early days of the internal combustion engine. Few of these apparently ever reached production, largely because of limitations of contemporary engine technology. The British Dunelt motorcycle, produced from 1919 to 1930, employed a simple version of the stepped-piston engine improve performance by increasing the displacement of the crankcase pump. This resulted in an excellent torque curve for which these machines became well known, at the expense, however or high fuel consumption. Technology Patents are held covering know-how in this technology. The engine offers low emission 2-stroke engine technology with the essential advantage of durability. The piston design proved crankcase isolation and therefore allows wet sump lubrication, plain bearings, low thermal loading of the piston, low manufacturing costs, a compact low-mass design and extended oil-change periods. Work has included design and development for automotive, defense, marine and industrial applications. Piston mass is naturally higher for a stepped piston design. However our unique approach means that for identical power cylinder bores the stepped piston is only around 20% heavier than a conventional looped scavenged two stroke piston. The multi section or step of the piston provides a flange stiffening effect resulting in thinner skirt sections. If necessary the mass increase can be reduced to fewer than 15% by composite methods. However the engine uses the two stroke cycle and therefore with the absence of load reversals piston mass is not as critical as it is for four stroke engines.

3.2 The Physical Concept

The piston geometry is as shown in Figure 3.1. It depicts the cross-sectional area of a two-piston engine synchronizing the induction and compression processes of a two-stroke cycle.

The stepped-piston concept overcomes some of the drawbacks of crankcase-compression engines. Increasing the delivery ration, isolation of the fresh charge from the crankcase and improving engine performance at high altitude are some advantages. The essential feature of the stepped-piston two stroke engines are shown in Figure 3.2.

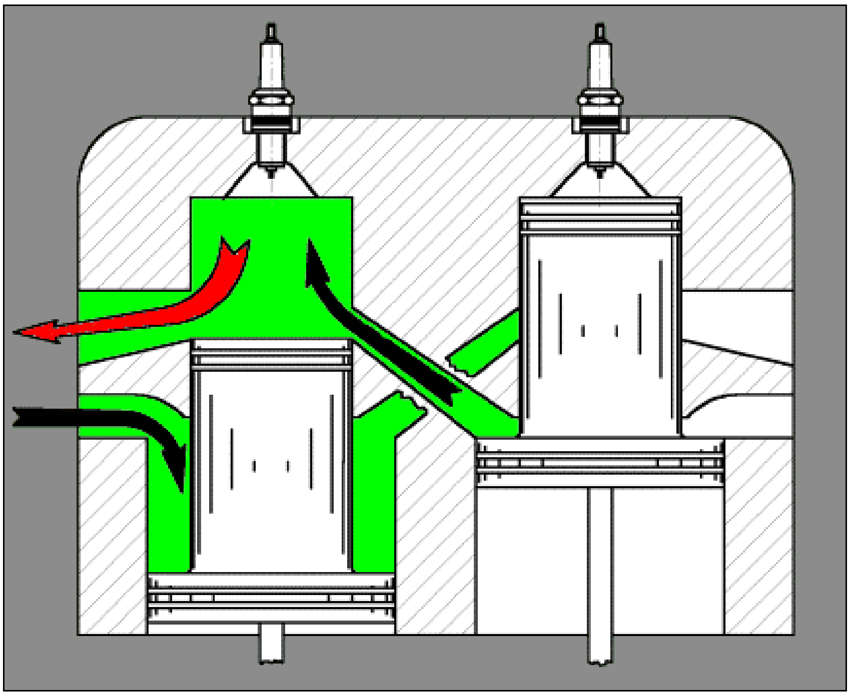


Figure 3.1: The stepped-piston engine as proposed by Bernard Hooper [9]

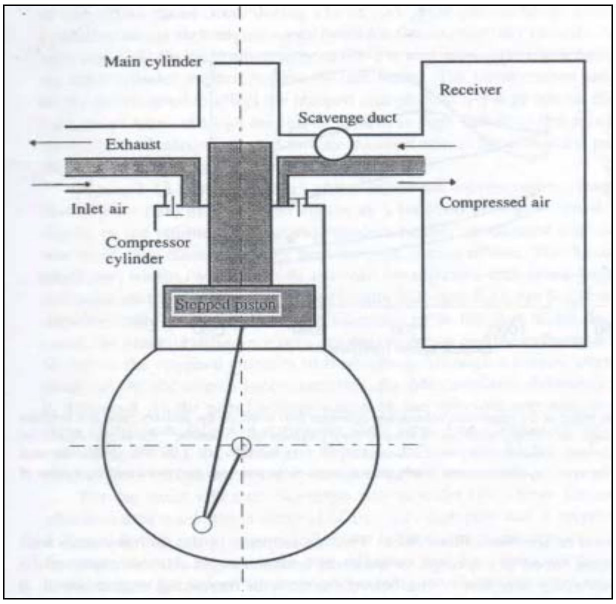


Figure 3.2: Schematic layout of a stepped-piston engine [9]

The engine is constructed of a stepped-piston and stepped cylinder, thus forming three compartments a power, a compression and crankcase compartment. With this arrangement, the fresh charge is compressed in the compression compartment, delivered to a receiver and introduced to the cylinder through the scavenge ports. In dome designs, the fresh charge enters the crankcase compartment prior to its admission to the cylinder. As the piston travels downward, the volume of the compression compartment increases, the pressure thus decrease and fresh charge is admitted. Meanwhile, the exhaust port of the power cylinder is exposed first then the scavenging port and the burnt gases inside the power cylinder are scavenged by fresh charge, which previously was compressed in the crankcase compartment. As the piston ascends, both exhaust and scavenged ports of the power cylinder are covered by the piston and simultaneously, the intake reed valve of the compression compartment closes, delivery reed valve opens and fresh charge flows from the compression compartment to the crankcase. Just before top center (TC), the fresh charge in the power cylinder is ignited, combustion occurs and the piston is pushed down for the power stroke.

For applications at high altitudes, it has been found that problem with the use of crankcase scavenged two-stroke engine is the sharp decrease in the engine power with increase altitude. This was attributed not only to low density of the ambient air, but also deterioration of the efficiency of the gas exchange process due the delivery ratio in the delivery ratio. The main reason for the decrease in the delivery ratio at high altitudes is inability of the crankcase volume to admit enough air when the pressure difference between the ambient and crankcase volume is small. Increasing the compression ratio of the crankcase is one possible solution, however the fresh charge supply to the scavenge ducts will most likely take place during only a small part of the scavenging period and the scavenging process would probably be less efficient. Increasing the delivery ration can easily be achieved with a stepped-piston engine.

Compared with the conventional crankcase scavenging engine, the stepped-piston engine offers better scavenging but higher pumping works, because both the compressor and the crankcase are required. If the increase in engine volume and weight are ignored, an optimal aspect ratio gives the highest thermodynamic efficiency exists. The engine's bulk however is an important parameter that directly affects specific power, usually an important feature of the two-stroke engine. Adding a compressor with high compression ratio at the inlet of crankcase appears to be an attractive solution. This modification facilitates breathing at high altitude (higher pressure difference between ambient and the compressor compartment), does not require a high aspect ratio (low engine bulk) and allows slower fresh charge delivery to the power cylinder during the scavenging period.

The advantages of a stepped-piston engine are as follows:

- Wet sump - conventional 4 stroke lubrication
- Plain Bearings
- No valve gear
- Low thermal loading of piston
- Low emissions with durability
- Low manufacturing costs
- Compact low mass design
- Extended oil change periods (oil does not degrade)
- Fast warm up (lower cold start emissions)
- Ability to operate on a wide range of fuels (including gas)

3.3 The Engine Design

The perspective view of the engine which was developed is shown in Figure 3.3.

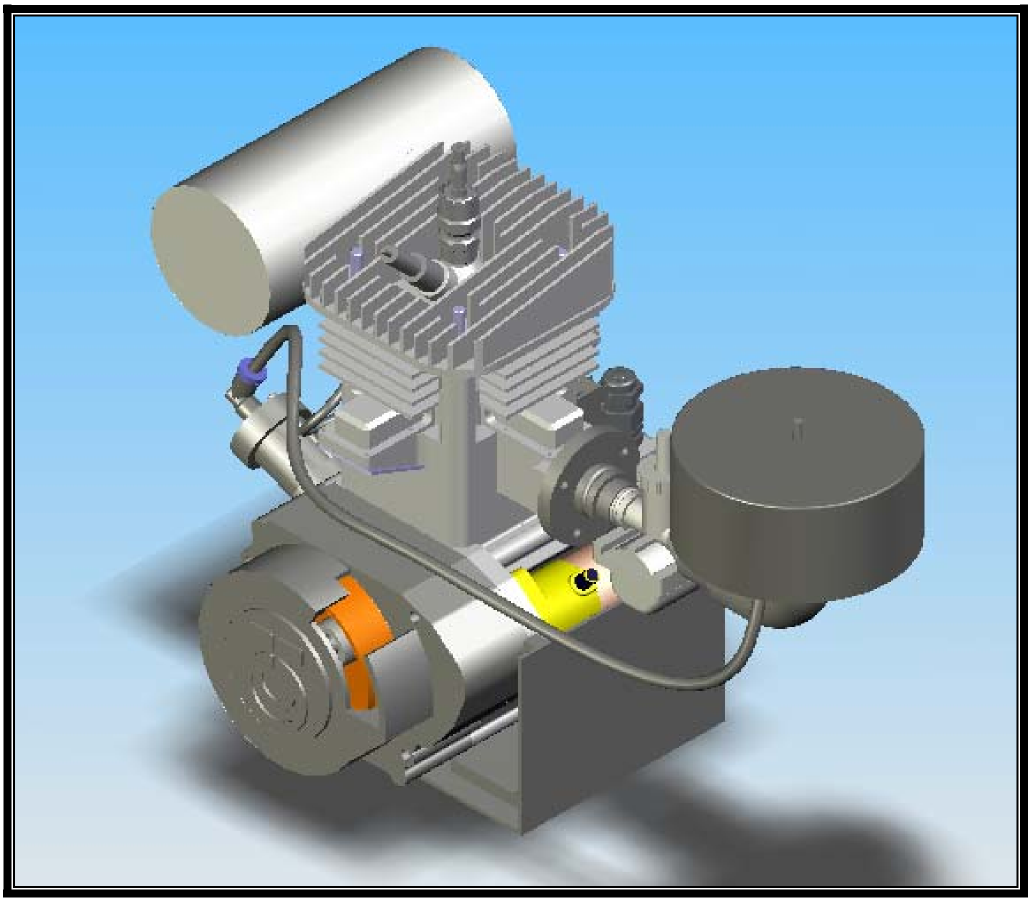


Figure 3.3: Perspective view of the Stepped-piston engine

Table 3.1: Engine specifications

	Parameter	Size/Feature
1	Cylinder type	Single cylinder, piston ported
2	Displacement	125 cm^3
3	Bore x Stroke	53.8 x 56 mm
4	Scavenging concept	Multi-port Loop Scavenging
5	Exhaust port opening/closing	93 CA ATDC/267 CA ATDC
6	Intake port opening/closing	110 CA ATDC/250 CA ATDC

7	Rated power (kW @ rated RPM)	9.2 @ 6500 RPM
8	Ignition timing	-20 BTDC

3.4.1 Critical Components

The following is a list of critical components found in most reciprocating internal combustion engines:-

3.4.1.1 Stepped-Piston

As mentioned earlier, the piston is unique from the perspective that is has a two pistons in one unit. The smaller but of wider diameter is attached at the bottom of the unit. The main piston resembles the piston in conventional crankcase scavenged engine.

Diameter upper = 53.80 mm
Diameter bottom = 81.92 mm
Height, H = 100.50
Material = aluminium alloy LM25

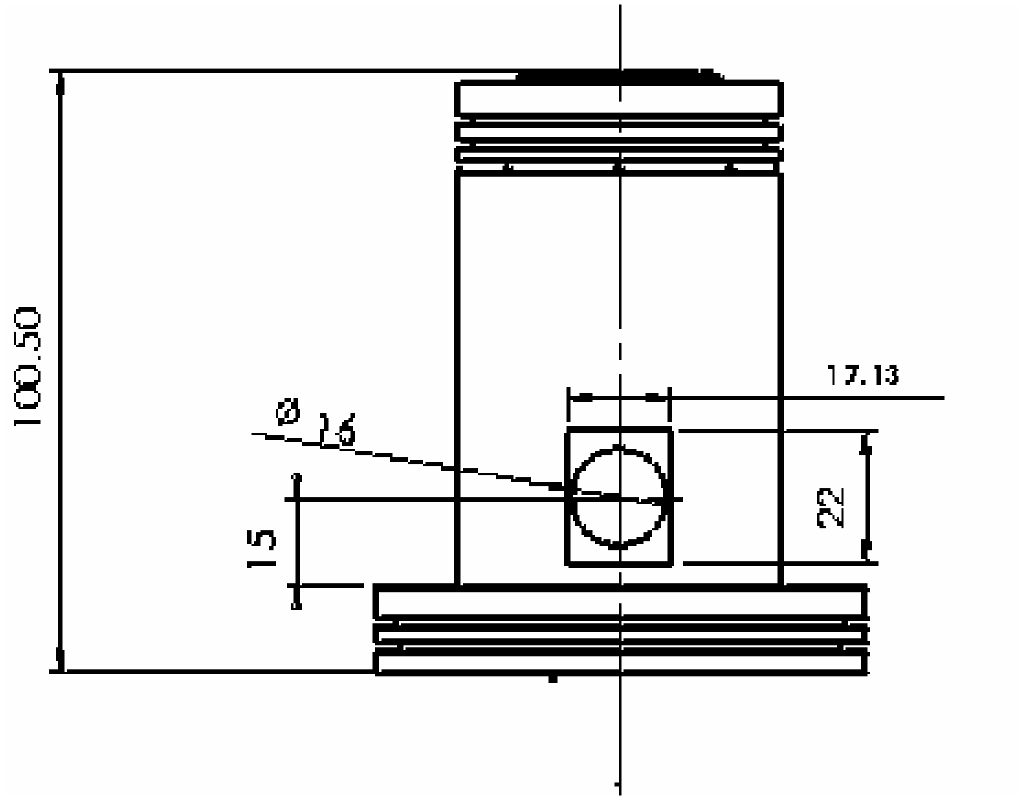


Figure 3.4.: Major dimension of the stepped-piston

3.4.1.2 Connecting Rod and Crankshaft

The connecting rod and its crankshaft are of conventional type with the crankshaft having a counterweight of circular type shown in Figure 3.5 below.

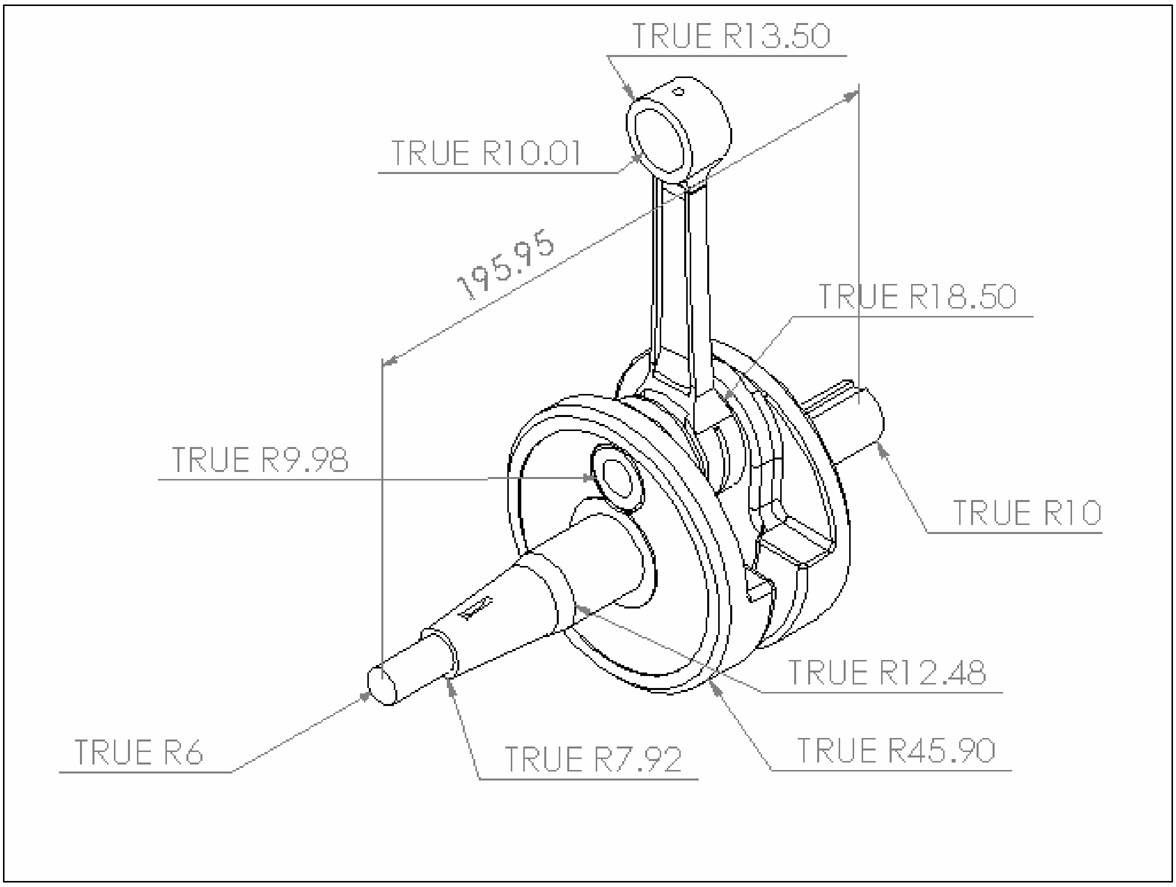


Figure 3.5: Dimension of connecting rod and crankshaft

The approach taken in the computation of the major parts of this linkage is as follows:-

$$s = a\cos\theta + \sqrt{r^2 - a^2\sin^2\theta} \tag{3.1}$$

$$a = \frac{s}{2} \tag{3.2}$$

where

a = crankshaft offset

r = connecting rod length

θ = crank angle

The major dimensions are:-

Connecting rod length = 110 mm

Diameter piston pin bearing = 20.01 mm

Diameter crankshaft bearing = 28.00 mm

Material = cast iron

3.4.1.3 Piston Pin

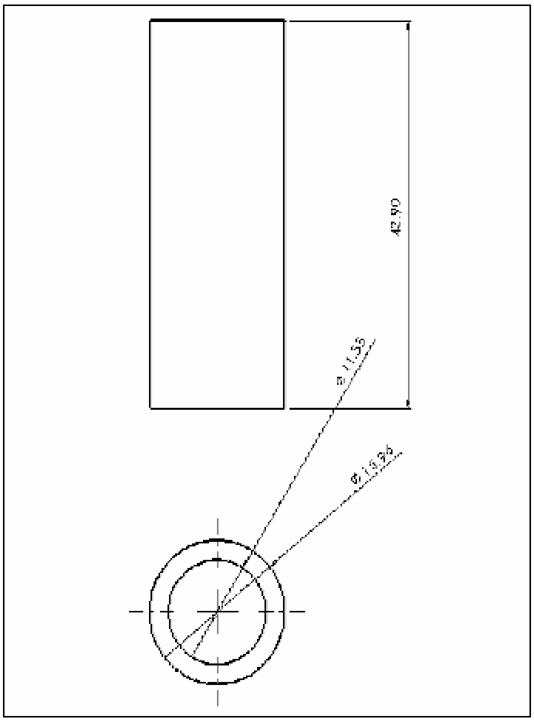


Figure 3.6: Dimension of piston pin

Piston pin length = 42.90 mm

Diameter piston pin, $_{outer}$ = 15.96 mm

Diameter piston pin, $_{inner}$ = 11.55 mm

Material = cast carbon steel

3.4.1.4 Cylinder Head

The engine cylinder head was decided on the basis of being light and able to discharge heat as a product of the combustion process effectively and having simple design. The major features are shown in Figure 3.7 below.

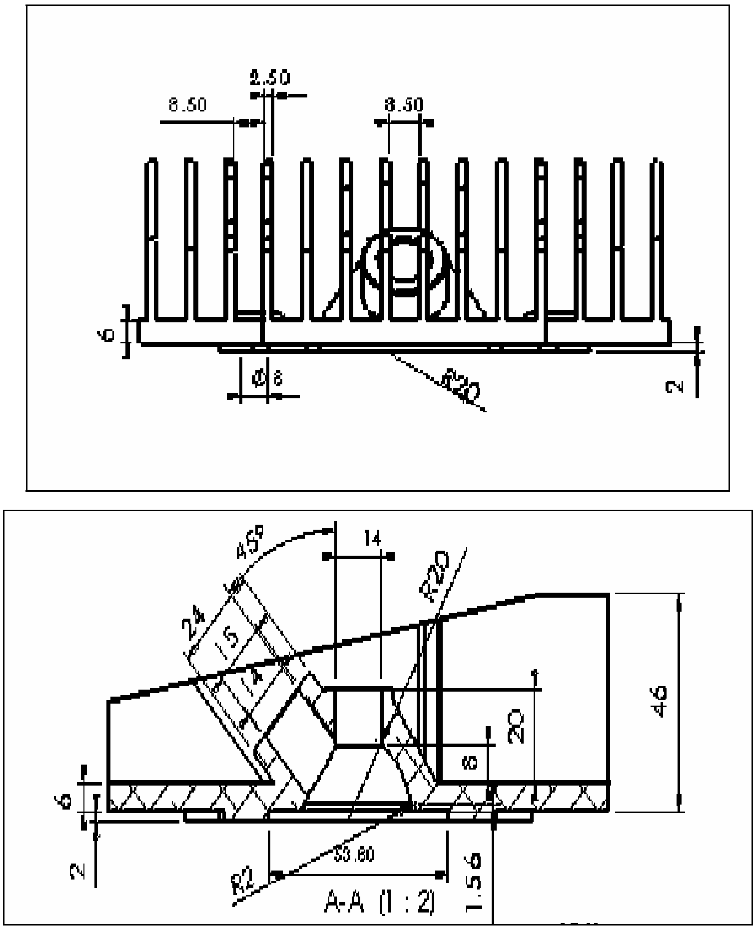


Figure 3.7: Dimension of cylinder head

It major dimensions are as follows:

Cylinder head length = 150 mm
Cylinder head width = 150 mm
Material = aluminium alloy LM25

3.4.1.5 Cylinder Liner

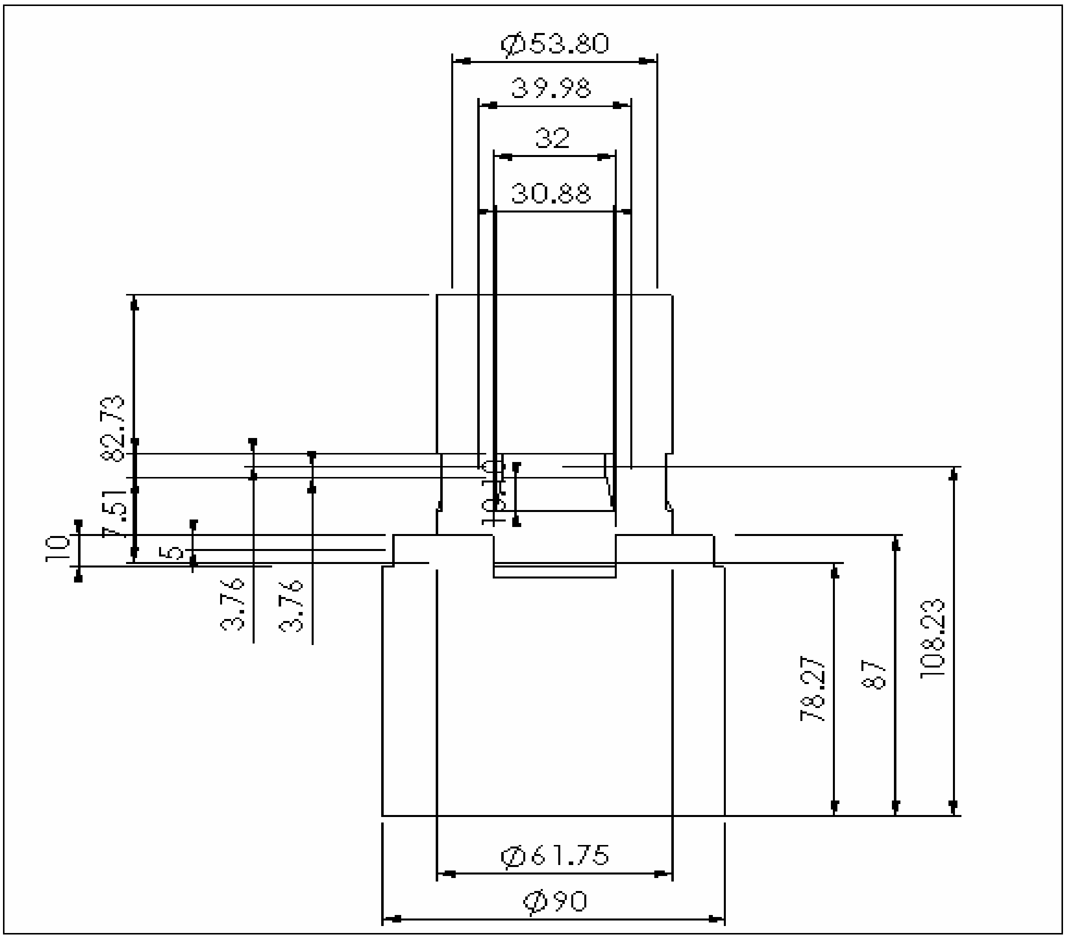


Figure 3.8: Dimension of the cylinder liner

The liners provide the surface for the contacts made by the engine piston rings onto permanent but removable parts in the engine main bodies.

The major dimensions of the liners are:

Height of upper = 82.73 mm

Height of bottom = 87.00 mm

Internal diameter upper = 53.80 mm

Internal diameter bottom = 81.92 mm

Material = cast iron

3.4.1.6 Cylinder Block

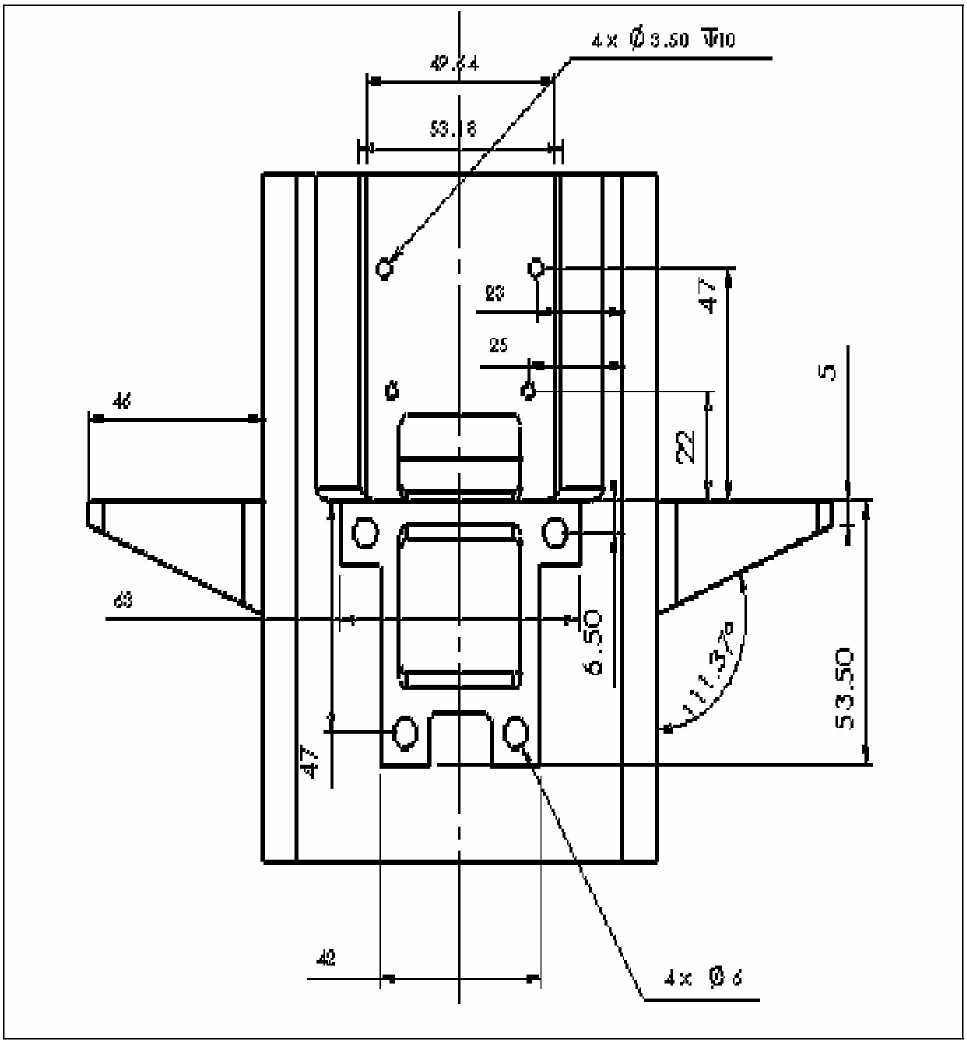


Figure 3.9: Dimension of cylinder block

Cylinder block is the major and by far the biggest component for this project. It accommodates the piston and the reciprocating mechanism for cyclic motion and performance. Some of the major dimensions of the engine block are:

- Cylinder block length = 139.00 mm
- Cylinder block width = 104.00 mm
- Internal diameter upper = 61.75 mm
- Internal diameter bottom = 89.95 mm
- Material = aluminium alloy LM25

3.4.2 Materials

Material selections constitute one of the major contributory factor to the successful engine development. Careful selection is necessary in order to render the engine functional, durable and reliable.

3.4.2.1 Aluminium Alloy LM25

LM25 is mainly used where good mechanical properties are required in castings of shape or dimensions requiring an alloy of excellent cast ability in order to achieve the desired standard of soundness. The alloy is also used where resistance to corrosion is an important consideration, particularly where high strength is also required. It has good weld ability. Consequently, LM25 finds application in the food, chemical, marine, electrical and many other industries and, above all, in road transport vehicles where it is used for wheels, cylinder blocks and heads, and other engine and body castings. Its potential uses are increased by its availability in four conditions of heat treatment in both sand and chill castings.

It is, in practice, the general purpose high strength casting alloy, whose range of uses is increased by its availability in the as-cast and partially heat-treated condition as well. It is used in nuclear energy installations and for aircraft pump parts. LM25 may be superior for castings, particularly in chill moulds, which are difficult to make to the required standard of soundness. It offers better mach inability and mechanical properties than LM6.

Table 3.2: Physical properties of aluminium alloy LM25

Coefficient of Thermal Expansion (per °C @ 20-100°C)	0.000022
Thermal conductivity (cal/cm^2/cm/°C @ 25°C)	0.36
Electrical conductivity (% copper standard @ 20°C)	39
Density (g/cm^3)	2.68
Freezing range (°C) approx.	615-550

Table 3.3: Mechanical properties of aluminium alloy LM25

0.2% Proof Stress (N/mm^2)	80-100
Tensile Stress (N/mm^2)	130-150
Elongation (%)	2
Impact Resistance Izod (Nm)	-
Brinell Hardness	55-65
Endurance Limit (5x108 cycles; N/mm^2)	70-100
Modulus of Elasticity (x10^3 N/mm^2)	71
Shear Strength (N/mm^2)	-

3.4.2.2 Cast Iron

Cast iron constitutes the bulk of the material content in the prototype engine. Cast irons are alloys of iron, carbon, and silicon in which more carbon is present than can be retained in solid solution in austenite at the eutectic temperature. In gray cast iron, the carbon that exceeds the solubility in austenite precipitates as flake graphite.

Gray irons usually contain 2.5 to 4% C, 1 to 3% Si, and additions of manganese, depending on the desired microstructure (as low as 0.1% Mn in ferrite gray irons and as high as 1.2% in pearlitics). Sulphur and phosphorus are also present in small amounts as residual impurities.

The composition of gray iron must be selected in such a way to satisfy three basic structural requirements:

i. The required graphite shape and distribution
ii. The carbide-free (chill-free) structure
iii. The required matrix

For common cast iron, the main elements of the chemical composition are carbon and silicon. High carbon content increases the amount of graphite or Fe3C. High carbon and silicon contents increase the graphitization potential of the iron as well as its cast ability.

Although increasing the carbon and silicon contents improves the graphitization potential and therefore decreases the chilling tendency, the strength is adversely affected. This is due to ferrite promotion and the coarsening of pearlite.

Other minor elements, such as aluminum, antimony, arsenic, bismuth, lead, magnesium, cerium, and calcium, can significantly alter both the graphite morphology and the microstructure of the matrix. The properties of cast iron are shown in Table 3.4.

Table 3.4: Cast iron properties

Description	Value
Elasticity modulus	6.618×10^{10} N/m^2
Poisson's ratio	0.27
Shear modulus	5×10^{10} N/m^2
Mass density	7200 kg/m^3 N/m^2
Tensile strength	1.517×10^8 N/m^2
Compressive strength	5.722×10^8 N/m^2
Yield stress	-
Coefficient of thermal expansion	1.2×10^{-5}
Thermal conductivity	45 W/mK
Specific Heat	510 J/kgK

3.4.2.3 Cast Carbon Steel

Carbon steels contain only carbon as the principal alloying element. Other elements are present in small quantities, including those added for deoxidation. Silicon and manganese in cast carbon steels typically range from 0.25 to about 0.80% Si, and 0.50 to about 1.00% Mn.

Carbon steels can be classified according to their carbon content into three broad groups:

Low-carbon steels: < 0.20% C

Medium-carbon steels: 0.20 to 0.50% C

High-carbon steels: > 0.50% C

Effects of carbon, the principal hardening and strengthening element in steel, include increased hardness and strength and decreased weld ability and ductility. For plain carbon steels, about 0.2 to 0.25% C provides the best mach inability. Above and below this level, mach inability is generally lower for hot-rolled steels.

Carbon steel castings are produced to a great variety of properties because composition and heat treatment can be selected to achieve specific combinations of properties, including hardness, strength, ductility, fatigue resistance, and toughness. The properties of cast carbon steel in Table 3.5. Although selections can be made from a wide range of properties, it is important to recognize the interrelationships among these properties.

Strength and hardness depending on alloy choice and heat treatment, ultimate tensile strength levels from 414 to 1724 MPa can be achieved with cast carbon and low-alloy steels. For carbon steels, the hardness and strength values are largely determined by carbon content and the heat treatment.

Table 3.5: Cast carbon steel properties

Description	Value
Elasticity modulus	2×10^{11} N/m^2
Poisson's ratio	0.32
Shear modulus	7.6×10^{10} N/m^2
Mass density	7800 kg/m^3 N/m^2
Tensile strength	4.825×10^8 N/m^2
Compressive strength	5.722×10^8 N/m^2
Yield stress	2.482×10^8 N/m^2
Coefficient of thermal expansion	1.2×10^{-5}
Thermal conductivity	30 W/mK
Specific Heat	500 J/kgK

Chapter 4

ENGINE AUXILIARY SYSTEMS

4.1 Breathing System

The gas flow processes into, through and out of the two-stroke engine are all conducted in an unsteady manner. In the case of exhaust induction flow into the crankcase through an intake port whose area changes with time, the intake pipe pressure alters because the crankcase pressure is affected by the piston motion, causing volumetric change in that crankcase. Stepped piston engine is one kind of two stroke engine developed to reduce emissions of the engine. Breathing system for a single-cylinder stepped piston engine is a mechanical part to transfer a pressure and to avoid the carry over of lubrication oil in the purged air from the crankcase. The system is related with the movement of the piston of the engine from top dead centre to bottom dead centre. A working process and high temperature that acts on the piston head and cylinder wall, and then provide the engine power output. As the result, the reaction produces a pressure in the crankcase which contain of lubrication oil. Therefore, the breathing system is very important to release and return back the pressures which come out with carry over of lubrication oil from the engine. A proper breathing system is required to provide a good efficiency of the engine.

4.1.1 Problem Statement

Two-stroke engines produce a degree of crankcase pressure mainly due to the gases from the combustion chamber passing the piston ring into the crankcase.

How worn the engine determines how much gas passes into the crankcase. Breathing system is very important process in every internal cycling process for a stepped-piston engine. It is the point of an engine to avoid the carry over of the lubrication oil from the engine while the engine is running. Although the carry over process reaction happen in a small volume for each second, but we have to avoid it and transfer the carry over of lubrication oil to suitable part of the engine for recycle process. Therefore, designing of the breathing system of the stepped piston engine is important to improve the performance of the engine.

Previously, most of the breathing process designing is done by experimentally and designing. The test needs some of the modern and sensitive apparatuses or equipment such as pressure transducer, tachometer and others to record the necessary parameter of breathing process. In addition, it is not economic and smart way if the test is repeated for every new design of the breathing system. Also, not all tests could successfully to carry out and the design needs to be improved from time to time.

In other way, the empirical method does not provide any of the vital information concerning the actually flow structure and chemical reaction inside the crankcase. Thus, the designers and engineer hardly to understand and predict the particular engine perform correctly or not. Therefore, Computational fluid dynamics (CFD) analysis is introduce to overcome the designs, while allow the users to obtain the breathing and flow information within a reasonable amount of time.

4.1.2 Objective

The objective of this project is to design and develop a breathing system to avoid the carry – over of lubrication oil in the purge air from crankcase for a single cylinder stepped piston engine, by using SolidWorks™ and *FLUENT*™ simulations and compare the results with that of the with experimental works.

4.1.3 Scope Of Study

The scope of this design and development work engulfed the follows:

1. Literature studies on the existing the breathing systems
2. Design of the breathing system
3. Draw the breather model by SolidWorks™
4. Simulate the flow process within the unit using *FLUENT*™
5. Develop the breather system
6. Testing the system on the engine.
7. Refinements

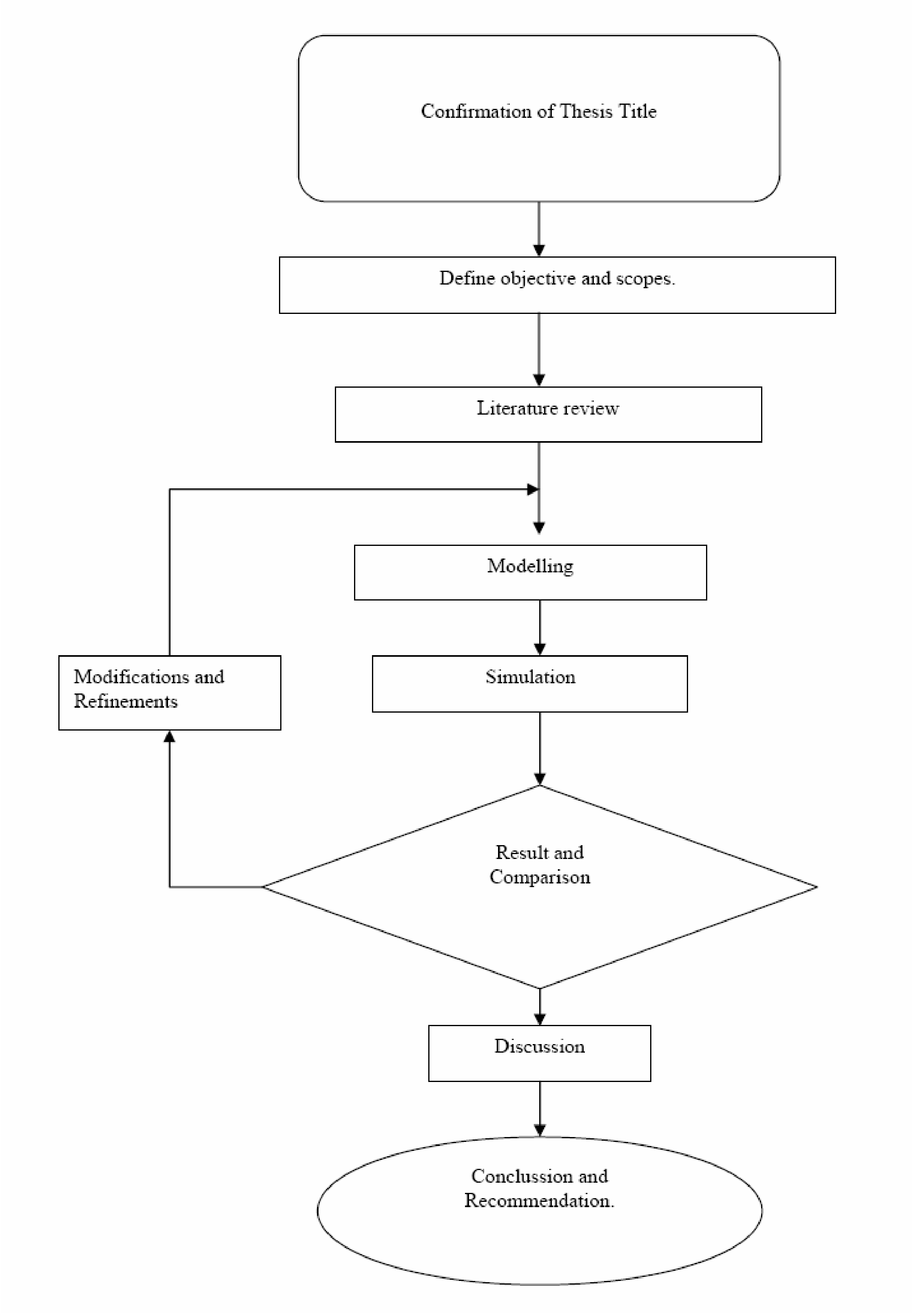


Figure 4.1: Work flow chart

4.1.4 Stepped Piston Breather Schematic diagram

The basic method of operation of the two-stroke engine and stepped-piston engine breathing system were already described. This chapter describe in detail of the breather system design proposed for stepped-piston engine.

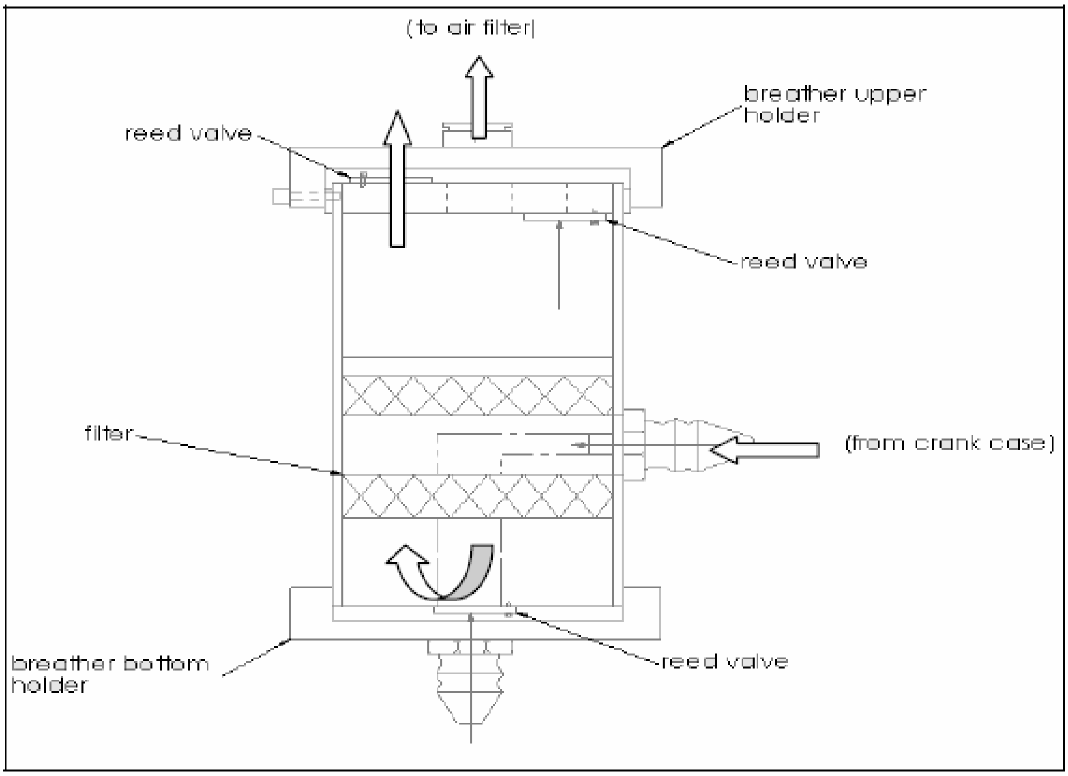


Figure 4.2: Breathing flow from TDC to BDC

In the above Figure, while the piston moves downward, the inlet part was closing by the piston during the down stroke. The exhaust port is been opened. The burnt gas has been sucked out from the chamber, through the exhaust port at above the piston part. The fresh air at the below piston part was compressing due to decrease of the crankcase volume and caused the increase pressure of the fresh air. This also causes the small pressure to be released out with carry over of lubrication oil to enter the breather through the inlet port. While enter the breather part, a lubrication oil was trapping by the filter located at the end of the

‘L’ part inside the breather. At the same time, the pressure was transferred to the air filter through the one way reed valve above the breather part while pressure inside the crankcase holding the reed valve from letting the lubrication oil return to the crankcase.

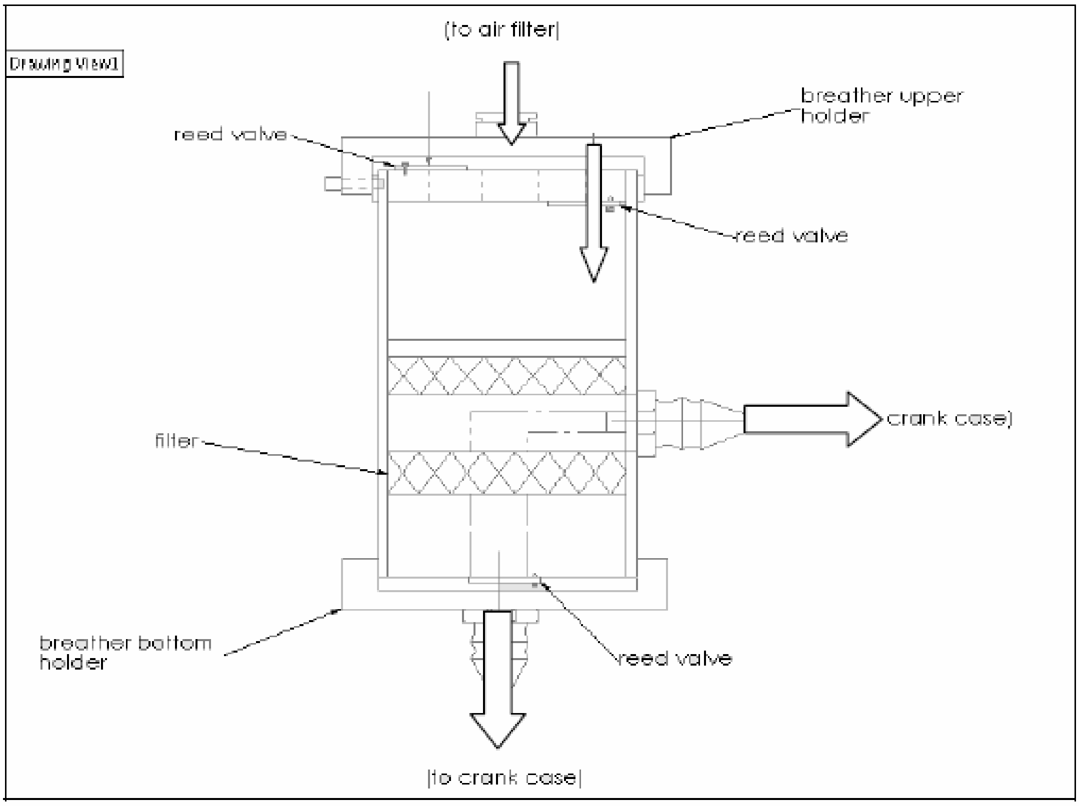


Figure 4.3: Breathing flow from BDC to TDC.

In Figure 4.3, while piston move upward from bottom dead centre (BDC) to top dead centre. The up stroke piston will close the transfer port and exhaust port. The air above the piston has been compressed and the pressure inside the chamber started to increase. At this time, the crankcase pressure was larger than the cylinder pressure and cause the fresh air enter the cylinder and pushed the exhaust gas out through the exhaust port. The fresh air enter the breather part through the inside reed valve above the breather cover and enter the crankcase through the bottom breather reed valve.

4.1.5 Rationale of the Proposed Design

The design of breather system for stepped piston engine was proposed according to its functions. This breather was designed for engine breathing process through the air filter and to trap a carry-over of lubrication oil come out with pressure from the crankcase. The filter inside a breather system will trapped the oil from the crankcase through the elbow part which attached with valve. The one way valve is located at the bottom and above the breather part. This one way valve will opened and let the pressure in and out with available pressure which measure by simulation and comply with experimental result. Besides this, the design was fabricated suit to the crankcase geometry.

4.1.6 Breather System connector

Figure 4.2 showing all the connector of a breather system for stepped piston engine according to breather system proposed design. There are two breather holders in this system. One is breather upper holder and another one is breather bottom holder. Both of this holder was fitted each other by using Allen key bolt (M3 x 55).

Bottom cover and upper cover are located at the end of breather body part. There are two petals which function as one way valve at breather upper cover. The outside valve will release the pressure to the air filter from a breather while the inside valve will allow the air to enter a breather system. One valve was fitted at the breather bottom cover. This valve will allow the pressure to enter the crankcase from the air filter. ‘L’ junction was located inside the breather body part. The junction was designed to allow the carry of lubrication oil from the crankcase trapped on the filter inside a breather and to avoid a vapour conditions at the air filter.

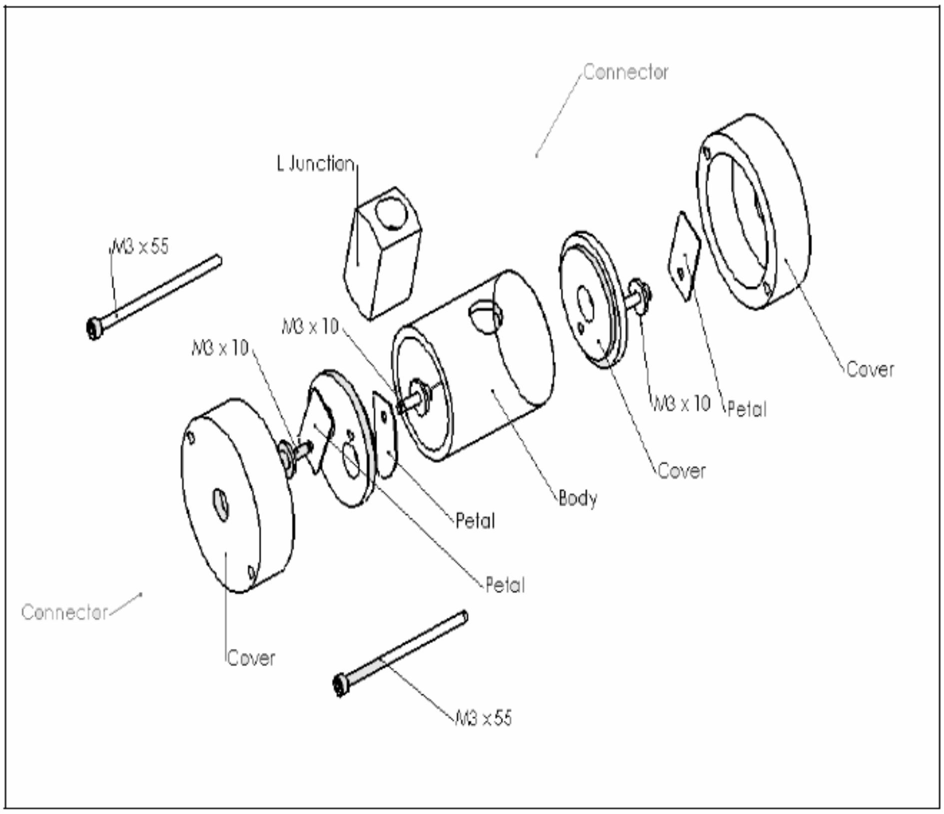


Figure 5.4: Connector of breather system

4.1.7 Modeling

Simple models of connector breather system of the stepped piston engine have been drawn by using SolidWorks™ (Figure 4.3). Later the models have been animated to the engine where the flow of lubrication oil occurs while engine running. Later model of breathing system have been modified to improve the appearance and performance of trapping oil. A 3D model has been drawn according to the actual model. Due to the difficulty to get the accurate measurement of the breather system, the dimensions have been modified according to the main dimension of the breather. The L part was selected as the part for *FLUENT*™ simulation to view the flow of pressure and the lubrication oil while the engine was running.

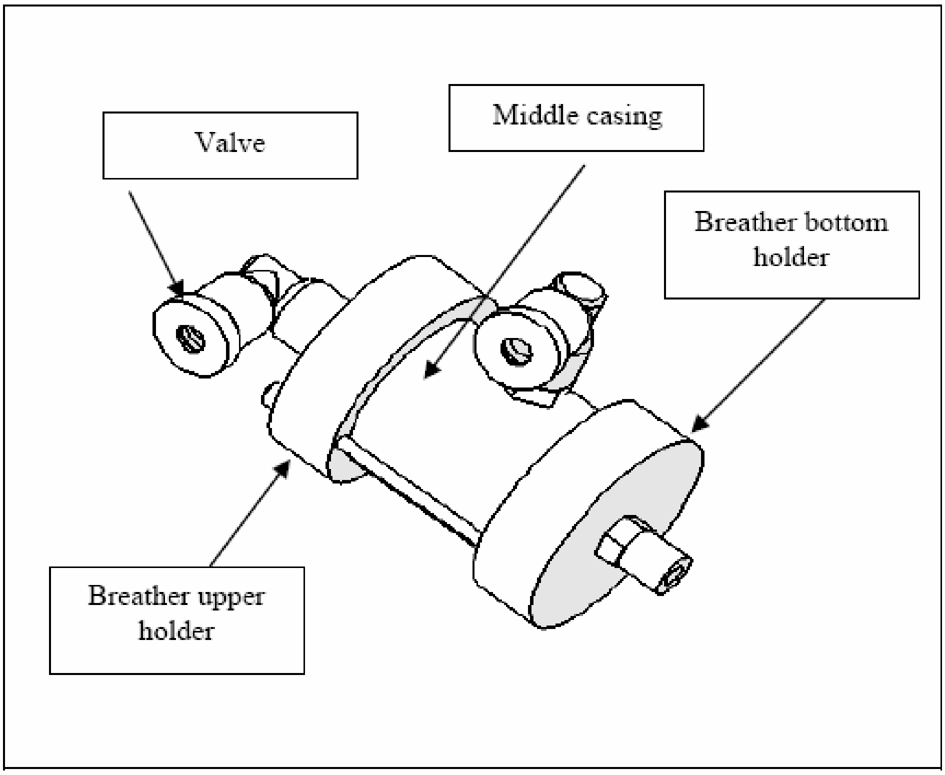


Figure 4.5: Assembly part of breather system

4.1.7.1 Model Meshing

The meshing has to depend on how accuracy that needed and the available computer resources, such as CPU time and storage capacity. A find mesh is required to improve accuracy of the computations.

The model of breather system with elbow part was exported to Gambit, a meshing computer program tool. The file is exported as ACIS file, which has file name extension of SAT. The gambit program was run under network program, which is Hummingbird Exceed.

The meshing of the model started from the line meshing (Figure 4.6), surface meshing (Figure 4.7) and finally volume meshing (Figure 4.8). All of the meshing is done in controllable mesh, where all the element sizes have been determine by the researcher. In the initial meshing, the total mesh elements are 11533 units.

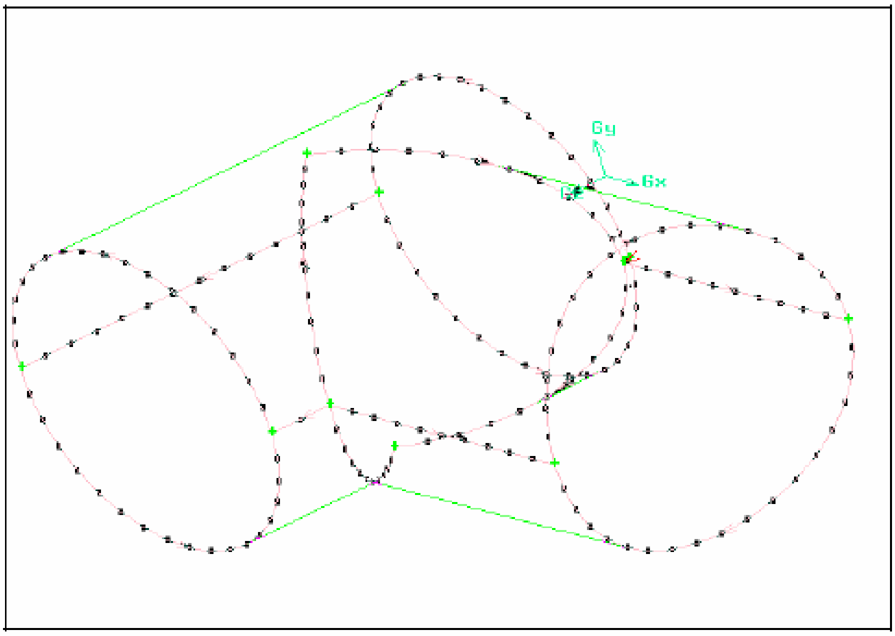


Figure 4.6: Line meshing.

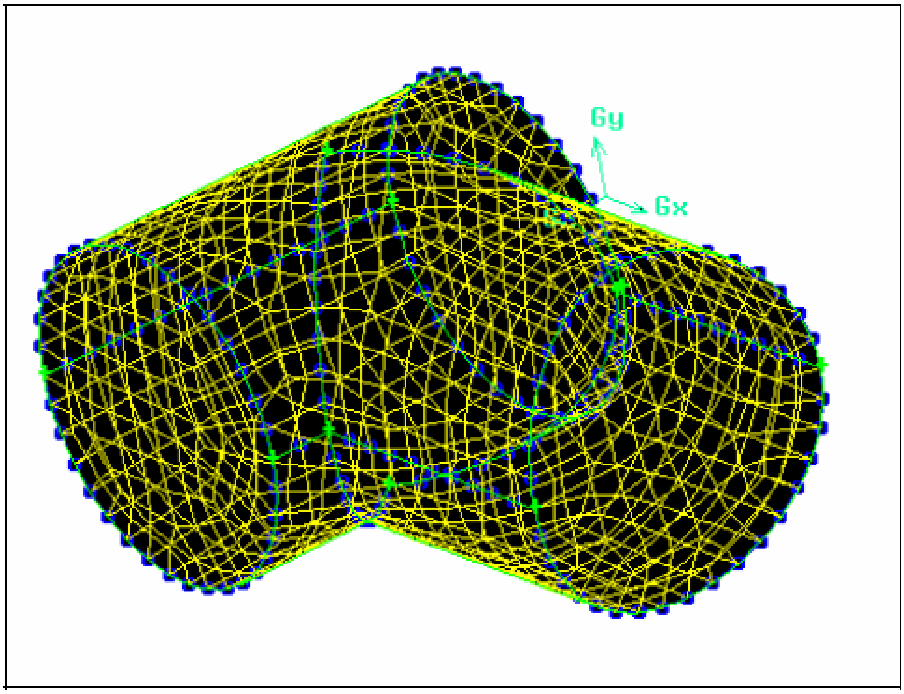


Figure 4.7: Face meshing.

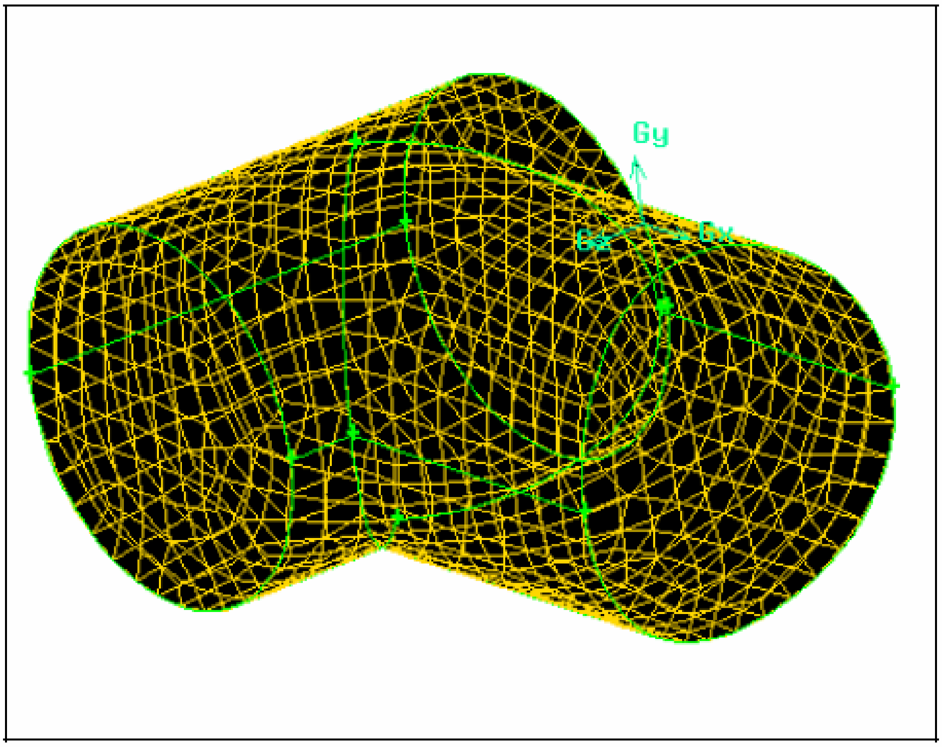


Figure 4.8: Volume meshing.

Figure 4.8 shows the volume meshing of the model. As shown in the figure, the model was meshed into to main shape of elements. There are triangle and rectangle elements. The meshing should be symmetry as it could to reduce the iteration time at *FLUENT*™. Thus, the proper control of line meshing (Figure 4.4) is important to determine the size of elements. Besides that, the edge ratio of face meshing (Figure 4.5) shouldn't more than 5, which means the longest edge in a element is than shortest edge 5 times.

After the complete meshed, the boundaries of the model were defined. As shown in Figure 4.9, all the outer surfaces were defined as static wall. While the interior surfaces were defined as interior, thus the fluid could flow freely among the volume.

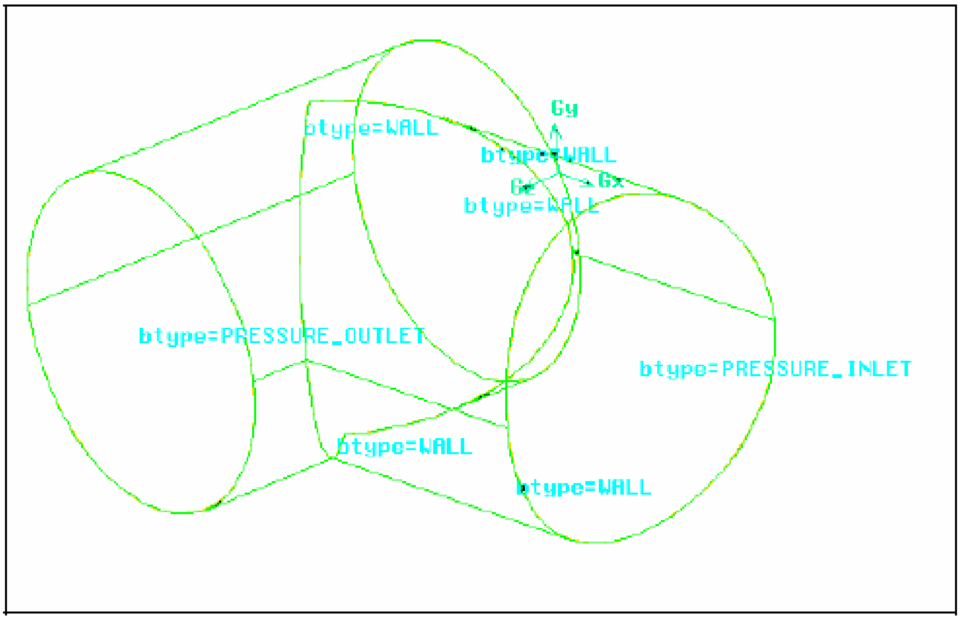


Figure 4.9: Boundary condition.

4.1.7.2 *FLUENT*™ Solution

FLUENT™ could solve the three-dimensional equations of fluid dynamics based on its Simple Algorithm. *FLUENT*™ allows the modeling of fluid flow, heat transfer and chemical reactions, by solving the equations for conservation of mass, momentum, energy and chemical species in control volumes, based on finite differences. The governing equations are applied on a curvilinear grid, for computation in irregular geometry. The physical model is based on turbulent flow. The calculation of finite differences in base of the equations of conservation is carried out as Reynolds average value of the correspondent laminar flow equations.

In summary the simulation for flow used four basic computer programs to assist the computation pressure and fluid dynamic simulation for stepped-piston engine breathing system. They are:

i) SolidWork™ for solid modeling

ii) *GAMBIT* for solid meshing

iii) *FLUENT*™ for breathing simulation

This section showed the methodology that the writer has been used to simulate the breathing process. The flow medium in this analysis is heavy liquid and and to monitor pressure flow. The liquid used in this analysis is an engine-oil, which will flow with pressure into a breather system through crankcase.

Breathing flow analysis should be analysis within k-epsilon model. Besides that, RNG would give more accurate result because it considered the turbulent inside the analysis, which has explained. This setting was done within the command Define-Model-Viscous.

4.1.7.3 Results of *FLUENT*™ Simulation

Figure 4.10 shows the scatter of pressure at different point starting from inlet port to outlet port through the elbow inside the breather. From the result, the high pressure condition occurred around the pressure outlet. It is because of the small volume of breather body part. The absolute pressure inside the breather after through the outlet port is around 1.18 bar equal to 120000 Pa. All this value equal to 0.18 bar according to the gauge pressure.

This mean that the experimental data pressure inside the breather is available to be transferred to the air filter via one way valve on breather cover. The lubrication oil passing the elbow part was trapped in a filter located between the bottom cover and the. The geometry of a breather system especially the elbow part will affect the flow of pressure inside a breather system.

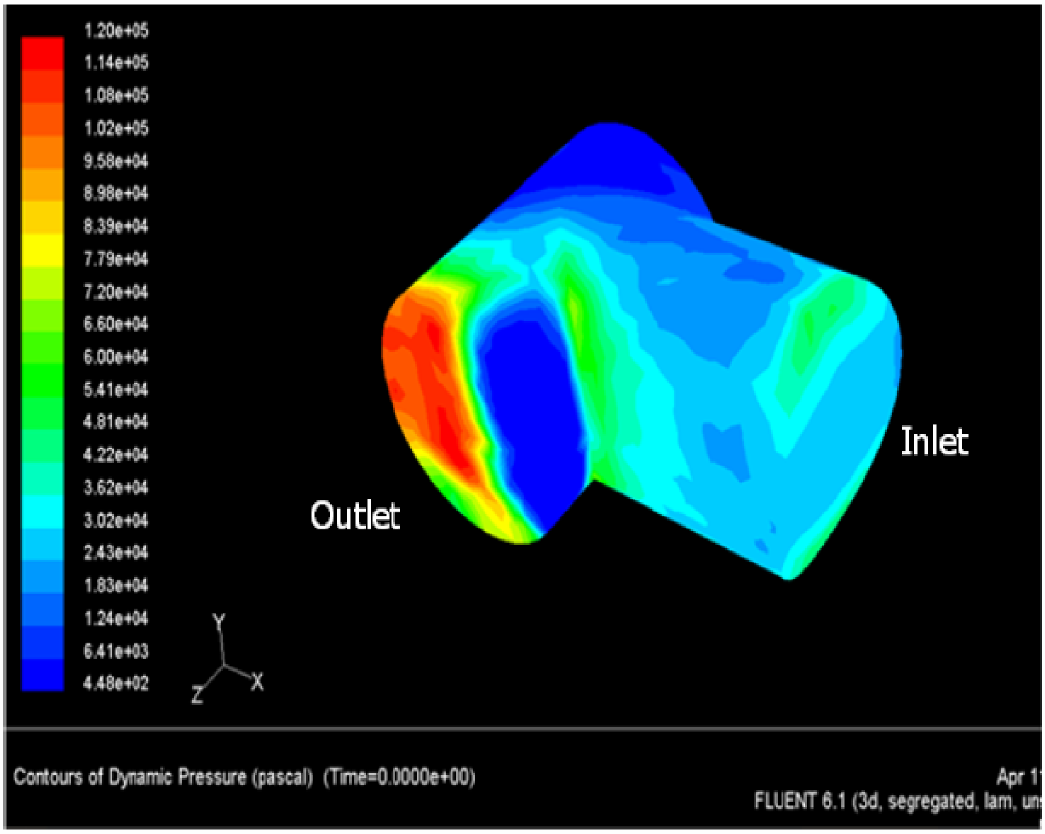


Figure 4.10: Contour of dynamic pressure.

Besides, a breather geometry and shape, oil trapping while a breathing process also influenced by volumes of lubrication oil contain in the crankcase either. Before running the engine, the lubrication oil must be refill to ensure it is enough for the engine running smoothly. However, sometimes the lubrication oil was refill more and caused the increasing amount of oil inside a breather. When unbalance quantity of lubrication oil added to the crankcase, the result obtained a small amount of oil enter a breather system. On the other words, the engine need an installation of mark point to determine the quantity of lubrication and to ensure it is always enough before running the engine. The oil separator tank should be mounted at or above the level of the top of the crankcase.

4.1.8 Experimental Method for Efficiency Determination

The empirical method also was done to determine the efficiency of breather system trapping the carry-over of lubrication oil volume manually. It is very important to determine the design of breathing system depends on the volume and pressure come out from the crankcase. The experiment was done by setup all the equipment of the engine especially a breather system. First of all it is very important to make sure a breather system was fixed tight to avoid oil leaking during the testing. By using weighing machine, the weight of a breather with all their part and the air filter was measured. Pressure inside the crankcase was measured using pressure transducer. The weight after running the engine for 1 hour was compared to previous weight before running the engine. From the experiment, the weight of lubrication oil trapped inside the breather could be determined. Besides, experimental method was further by measured the available pressure to pressed the petal (valve) to opened and let the pressure through the breather. This experiment required a modification equipment to get a better result. The main equipment is like pressure gauge and dial gauge. Before starting the experiment, the equipment need to be setup to attached a breather with both pressure gauge and dial gauge. Pressure gauge will give variable pressure reading and dial gauge will give the dimensions of petal opened to let the pressured through itself (Figure 4.11).

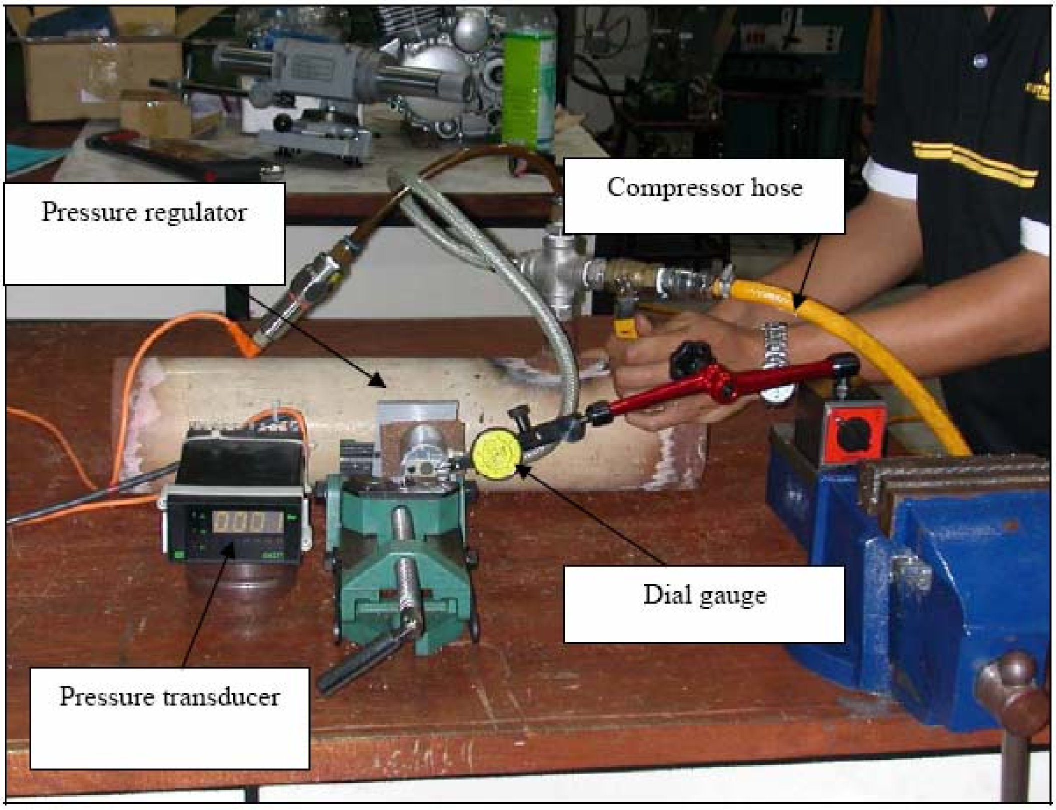


Figure 4.11: Pressure testing setup

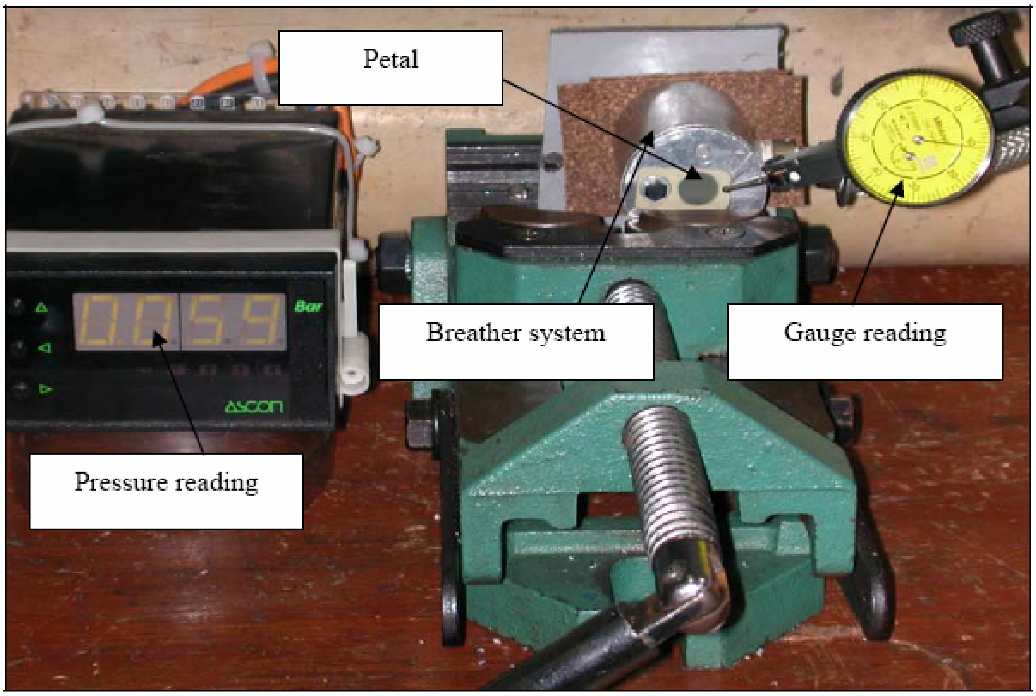


Figure 4.12: Pressure and petal deflection reading

4.1.9 Experimental Results

Table 4.1: Engine breather testing data 1

Speed (rpm)	Duration (minutes)	Breather + filter weight (kg)	Oil trapping (kg)
0	0	0.433	0
1089	15	0.437	0.004
1100	15	0.439	0.006
1165	15	0.441	0.008
1200	15	0.443	0.01
1250	15	0.444	0.011
1326	15	0.444	0.011

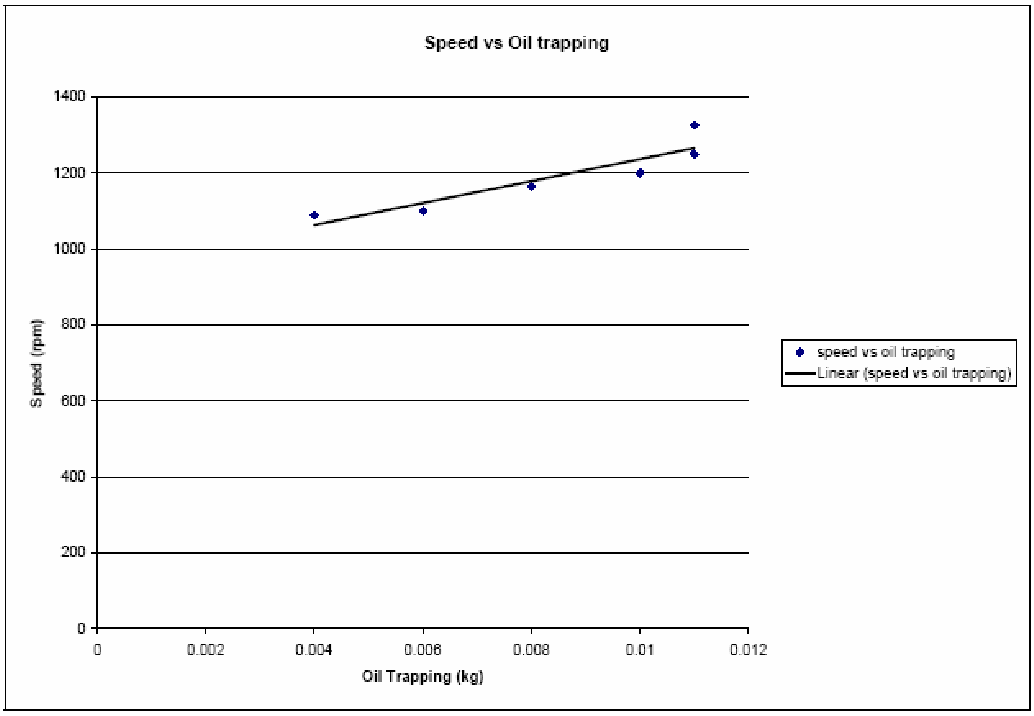


Figure 4.13: Graph of speed against mass of oil trapped

From the experimental data (Table 4.1), the engine was running for 1 1/2 hour with a breather fitted on it. The data shows that the engine was running on variation of speed and has been paused every 15 minutes to measure oil trapped inside the breather. This method was repeated until the mass of trapping oil is constant although the engine is running further. From the experiment, mass of lubrication oil inside the breather were defined increase with functional of time every 15 minutes and constant or stopped flowing through the breather after 1 hour. The condition of a breather system will influence the quantity of oil trapping. A breathing system should be always in a tight condition and ready to use to avoid leakage of pressure and carry over of lubrication oil. A breather trapped the carry-over very well after modification by adding the oil ring between the breather cover and the breather holder.

Table 4.2: Engine breathing testing data 2

Speed (rpm)	Time Running (minutes)	Lub oil Discharge (kg)
1500	5	0.001
2000	5	0.001
2500	5	0.001
3000	5	0.002
3500	5	0.001

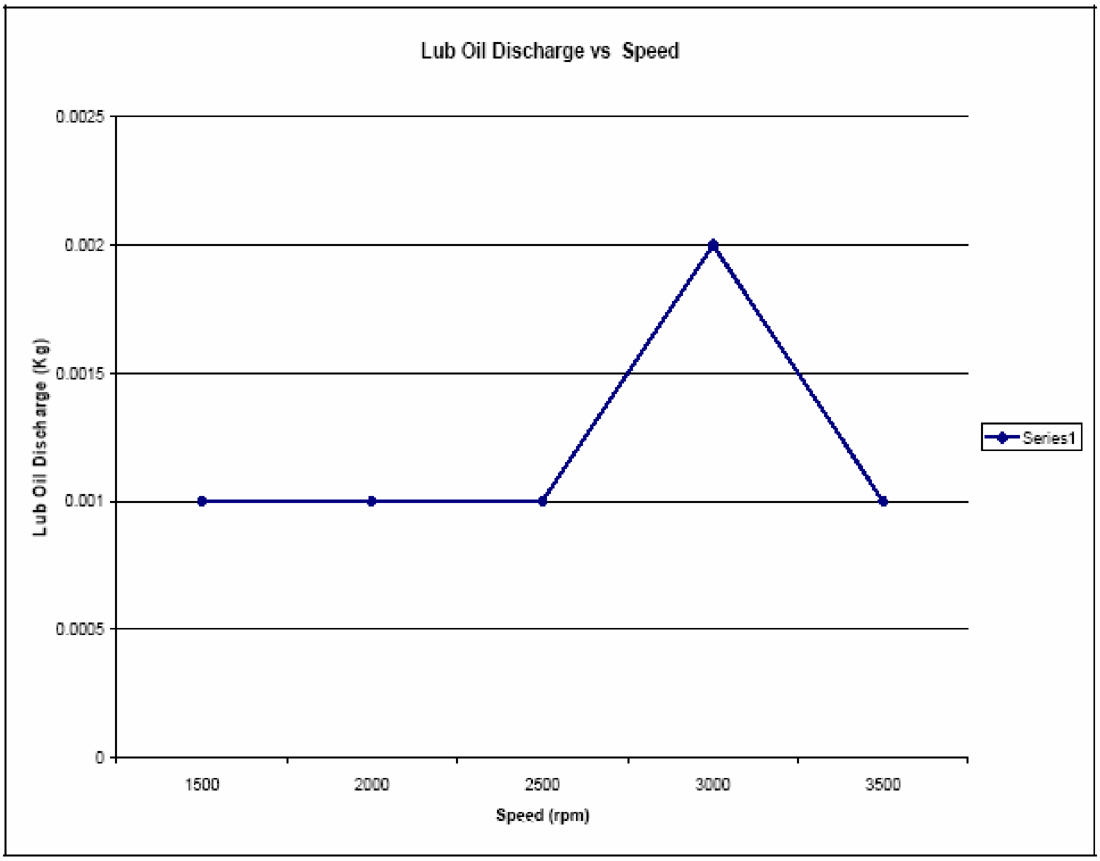


Figure 4.14: Graph of lubrication oil discharge against speed

For the second testing, the engine was running for 5 minutes for each time. Then, the weight of the breather was measured rapidly. The objectives of the experiment is to determined either the breather design must be the breather with functional of speed. From the result shows that for any variation of speed, lubrication oil discharged constant with speed. Breather system trapped a small amount of lubrication oil from the crankcase. It is very difficult to design a breathing system with functional of speed. It means, for each rpm the engine need a different breather to be operate. Therefore, it's not necessary to design a breathing system with functional of speed.

Table 4.3: Petal deflection data

Pressure (bar)	Petal deflection (mm)
0.056	0.1
0.085	0.175
0.112	0.2
0.14	0.25
0.173	0.3
0.236	0.38
0.449	0.45
0.5	0.51
0.621	0.58
0.607	0.68
0.672	0.95

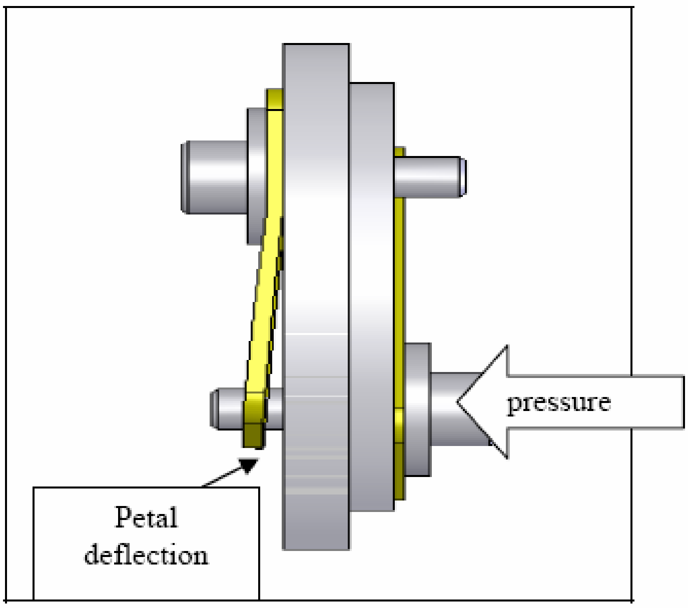


Figure 4.15: Petal on breather cover

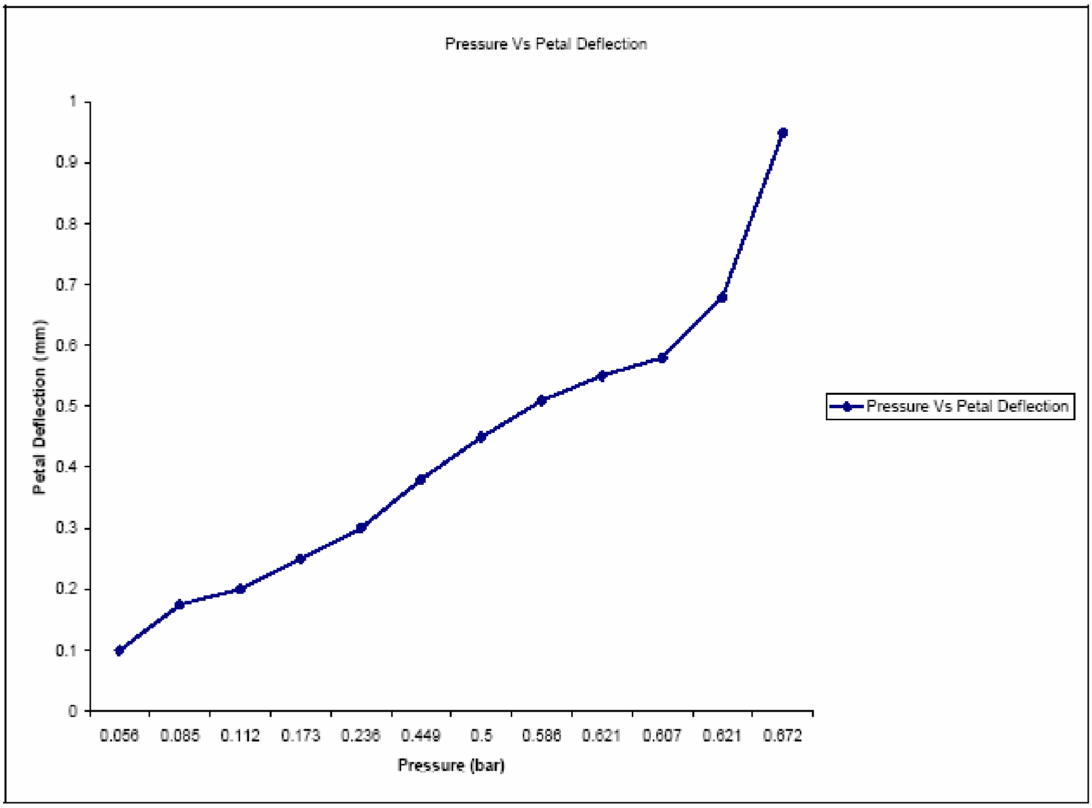


Figure 4.16: Graph of petal deflection against pressure

Table 4.3 shows the data of petal deflection during pressure testing on breather valve. The objectives of this experiment is to determined the petal deflection on breather cover when pressure through itself. The results were compared with pressure calculated from simulation with *FLUENT*™ to confirm either the pressure value is available to press the petal to open.

The data shows that the minimum pressure to deflect a petal is 0.056 bar. With this value of pressure, a petal deflected about 0.1mm and let the air through itself.

4.1.10 Breather System for the Stepped Piston Engine

Pressure builds up in the engine crankcase due to vapour from the hot engine oil and also from exhaust gases that escape past the piston rings (this will be more apparent in a high mileage engine where the piston rings are starting to wear). A crankcase breather system is used to release this pressure. The main reason by adding a breather system is to avoid the lubrication oil from overflow to the piston sleeve due to the stepped piston movement. To avoid the polluting effects of allowing the oil vapour to escape directly into the atmosphere, the breather feeds the crankcase gases into the engine where they are burnt and so converted to less harmful compounds. Fitted into the oil separator is a plastic one way valve. This is a push fit (using an Oil ring seal) into the outlet pipe of the oil separator with a plastic securing clip. Fitted to the other side of the valve is a rubber pipe which joins the large diameter supercharger air return pipe between the throttle bypass valve and the cam cover. From here the oil vapour and other gases are sucked in by the supercharger and eventually end up in the combustion chambers to be burnt. The one way valve prevents air being forced back into the crankcase under conditions where the crankcase pressure is lower than that in the breather return pipe. If the breather system becomes blocked the crankcase pressure will build up. The only way out for the gases is via the dipstick tube which tends to throw out lots of liquid oil as well.

It is extremely important for both engine oil control and performance that the crankcase breathing system be clean and functional at all times. A clogged or inoperative crankcase ventilation system will lead to poor engine performance, rapidly wear out rings and cylinder bores, stick rings, valve lifters, valves, and cause sludge formations which can clog oil passages throughout the engine.

Most recent engines are equipped with a positive ventilation system, which means that the engine is a sealed unit as far as crankcase fumes and pressures are concerned. The fumes, blow-by, and other crankcase by-products are recirculated through the fuel intake system, burned with the fuel, and subsequently expelled through the exhaust system. Older engines are equipped with a ventilated oil filter cap which allows fresh air to be drawn into the crankcase. There is a partial vacuum induced in the crankcase by having a breather pipe extending toward the bottom of the engine, which by the shape of the pipe opening and the movement of the vehicle, a low pressure area is created to draw the fumes, blow-by, and combustion by-products out of the oil.

4.2 Capacity-Discharge Ignition (CDI)

The CDI system was selected for the engine as its ignition system. The CDI system which is also called “thyristor ignition” operates on a different principle from conventional ignition coil system. This system was developed for high-speed and high-performance reciprocating engine for sport and utility engines.

The essential feature of a capacitor-discharge ignition system is that the ignition energy is stored in the electric field of a capacitor. The capacitants and discharging voltage of the capacitor determine the quantity of stored energy. The ignition transformer transforms the primary voltage generated by the discharge of the capacitor to the required high voltage. Capacity-discharge ignition systems are available in breaker-triggered and breakerless designs.

The main advantage of CDI is its high degree of resistance to electrical shunts in the high-voltage ignition circuit, particularly those which occur at fouled spark plugs. For many applications, the spark duration of 0.1 to 0.3 ms is too short to ensure reliable ignition of the air-fuel mixture. For this reason, the CDI system is designed only for this specific high-speed engine.

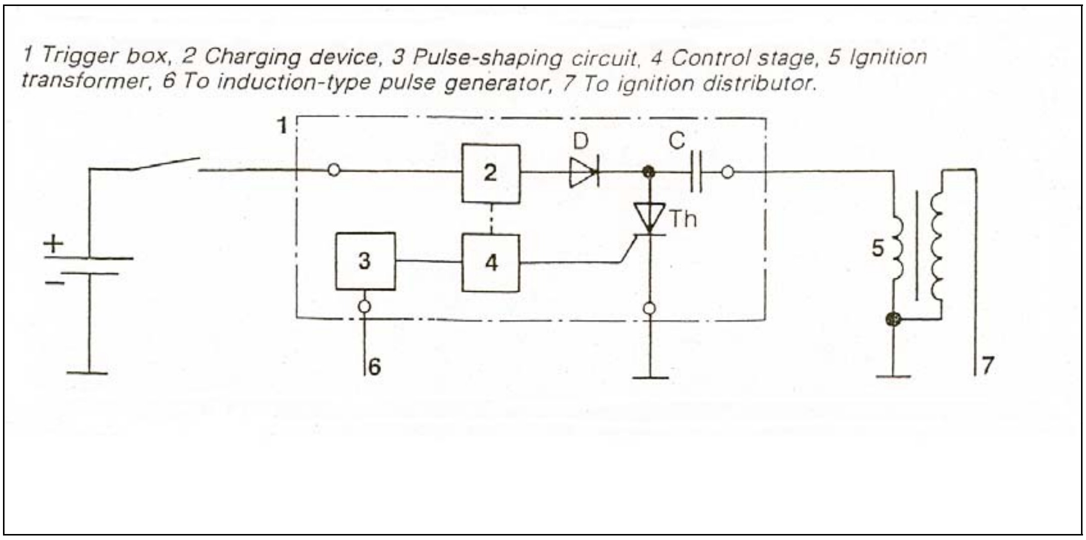


Figure 4.17: The schematic diagram of the engine's capacity-discharge ignition (CDI) unit [10]

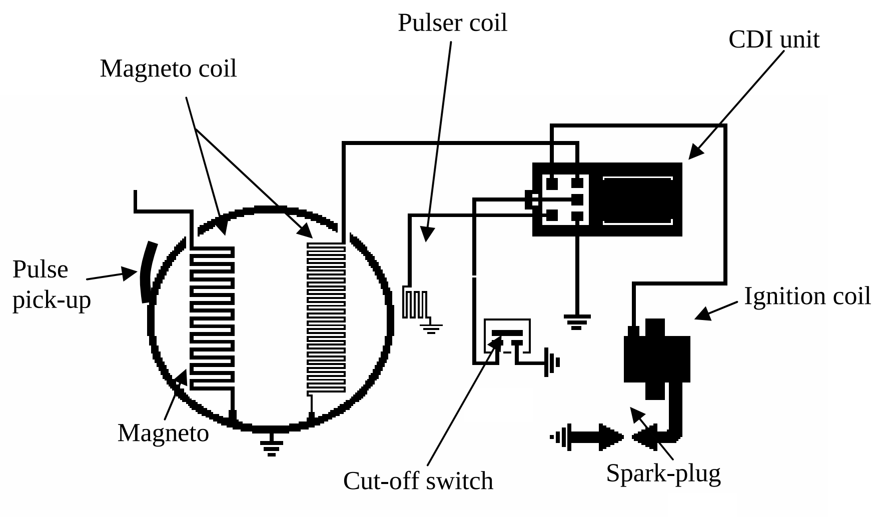


Figure 4.18: The ignition system for the stepped-piston engine

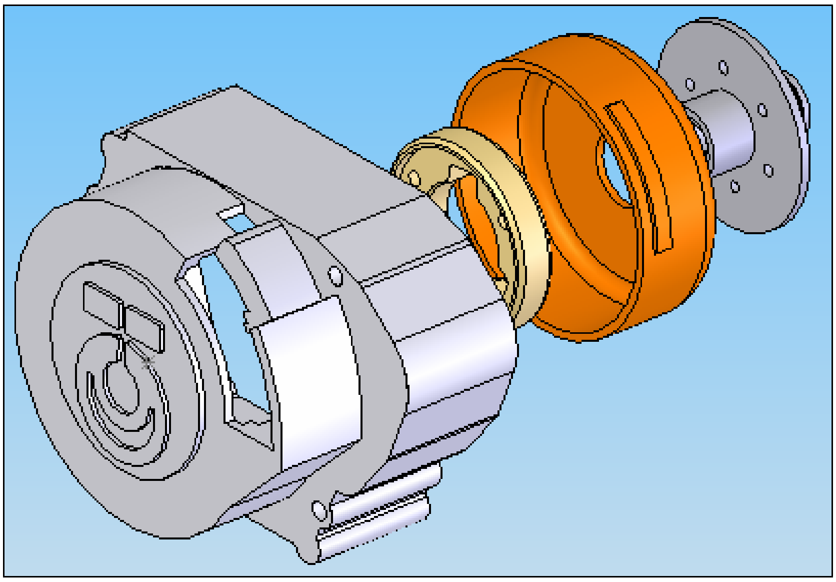


Figure 4.19: The exploded view showing the ignition system enclosed in the engine's front cover

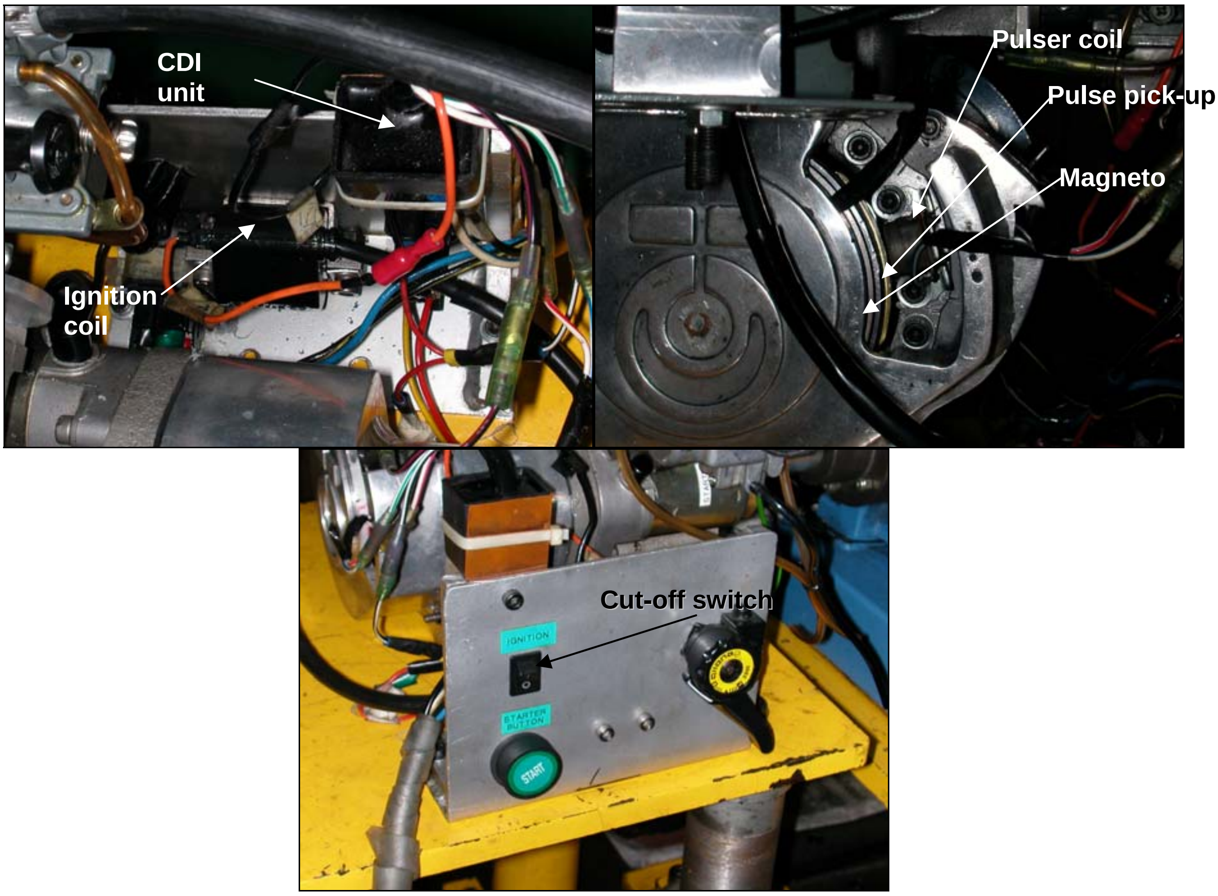


Figure 4.20: Photographs showing the ignition system embedded on the engine

4.3 Add-on Module

This is an auxiliary add-on component specifically designed to convert the carbureted version into a fully fuel-injected version equipped with a lubricant dispenser unit. This unit is mounted on the front of the engine with little problem in adaptation. With the mounting of this unit it will add an addition weight of 1.75 kg to the engine. It was made of aluminum alloy for weight consideration where it accommodates several components i.e. i) solenoid valve for fuel supply, ii) fuel accumulator, iii) housing for high-pressure pump and iv) gear pump for the lubricant dispenser.

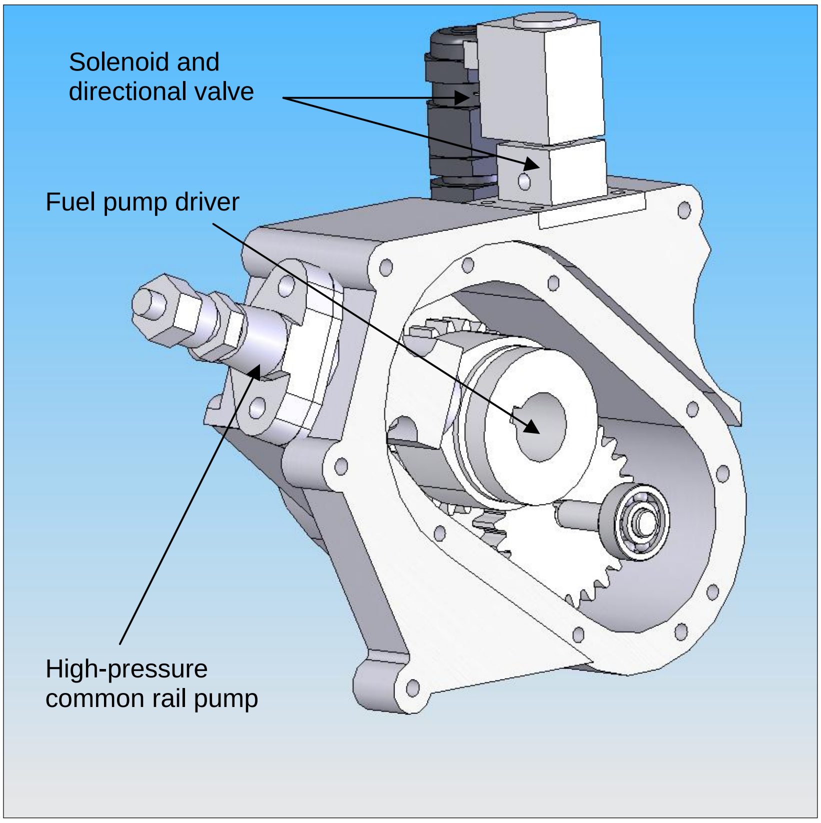
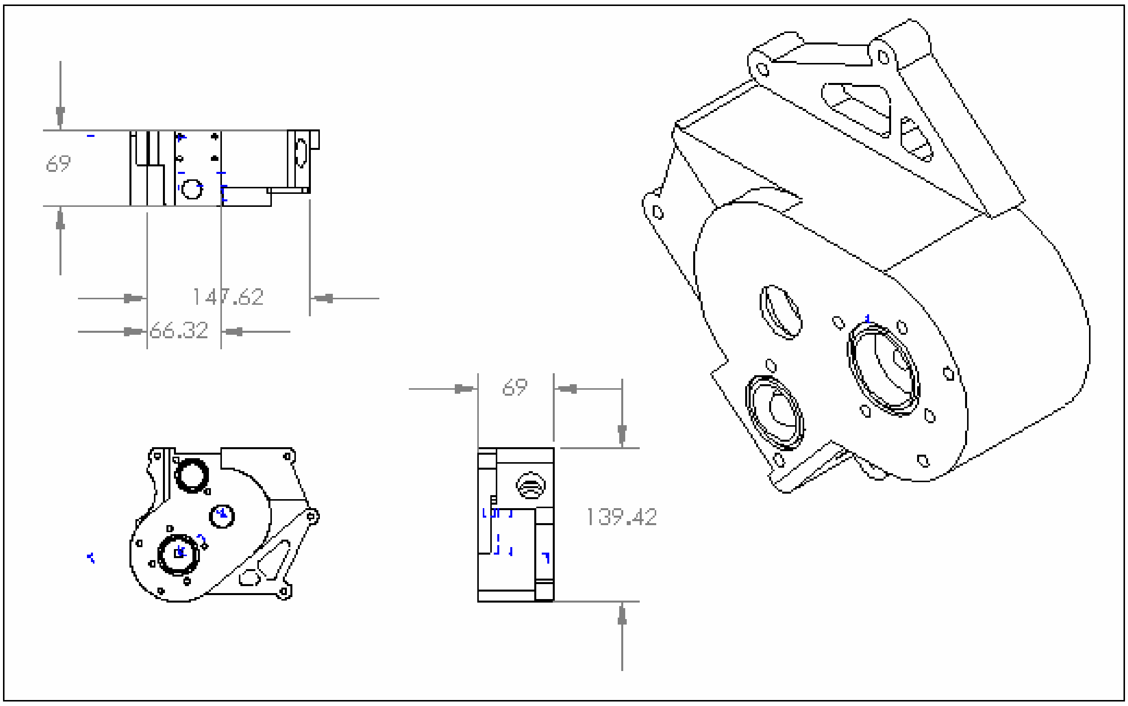


Figure 4.21: The add-on module



4.22: The detail drawings

Figure 4.23: The close-up of the add-on module.

Chapter 5

ELECTRONIC FUEL INJECTOR CONTROLLER

5.1 Introduction

Engine motorcycle faces to the heavier environment compared to car's engine. The electronics must be protected from impact and vibration. Locking the circuit inside a sealed, die-cast aluminum box is must. Cable entry would need to be via waterproof cable glands. The aluminum box would also provide an effective heat-sink (as long as it wasn't mounted too close to the exhaust pipe). Foam inserts (rather than solid screw mounts) could protect the board from vibration, although having a bunch of components bolted to the case might stop this working.

Engine electronic control (EEC) is designed a compact unit and to be applicable and directly installed into a small engine. It contains a printed circuit board (PCB) with electronic components. The CPU with onboard RAM, and ROM should do as much as possible, thus minimizing interface components. PWM for fuel injector is done by a timer which has been programmed to control the output pulse width. A multi terminal plug connects the EEC to its sensors, injector, as well as to its power supply. The EEC must withstand high temperatures, humidity and physical stresses.

The electronic components in the EEC are arranged on PCB; the output stage power components are mounted on the metal frame of the EEC thus assuring good heat dissipation. The EEC is more cost effective because of its low parts count due to integrated technology, simpler to install because of its generic design and flexible software. It allows to be used with all models and makes of engines from motorcycles to trucks, even or odd number of cylinders. The reliability of the EEC is increased by combining functional groups into ICs and by properly selecting in electronic component.

This embedded controller is designed for A/F ratio control and the fuel injection actuation. The methodology lookup table is adopted for this controller.

The design will consist of a series of processes that respectively process data, and make control decisions. The allocation of the processes to physical entities creates the system architecture. A concept of the engine as a means of developing torque is used as the physical architecture. The software architecture emerges from an analysis of what the system is required to do and is a collection of processes. The system architecture is the end result of the design process and consists of the processes and the physical hardware to which they are assigned.

5.2 Hardware Design and Development

The hardware design and development of EEC involves several steps; define the task, design and build the circuits, write the control program, test and debug. For ease of understanding the individual tasks, characterized data has been included that shows standard microcontroller CPU and I/O requirements of each function. The data presented here was obtained through intensive simulations with some common general market architectures using real engine traces as a source of simulation input. The Figures also assume that all control tasks will be handled by a single processor.

- Injection: pulse width and multi pulse calculations for direct and port injection systems relative to a crank angle.
- Tooth management: camshaft detection and crank shaft tooth detection with recalculation of engine rpm and acceleration and thus update of time/angle and angle/time events.

- A/D conversion: it will be required with 8 bit resolution for a range of MAP sensor and minimize execution times. MAP sensor chosen has a range of 1 to 5 bar. It is mostly used for vehicle. The core of A/D converter has four independent execution units that can operate in parallel. Consequently, the instruction sequencer keeps the A/D converter busy by fetching the instructions, decoding and then issuing to the corresponding execution unit. Advanced features such static branch predictions, branch folding and interlocked pipelines, further improve the performance of the core.

The selection of microcontroller chip used is based on a specific project. All microcontrollers contain a CPU, and each device family usually has different combinations of options and features, ROM or EPROM, and with varying amounts of RAM. In this research, 8051/8052 family of microcontrollers which includes chips with program memory in ROM or EPROM is chosen. It is an easy to use, low cost, and versatile computer on a chip. Other factor consideration is this type of microcontroller dominated the market share [11]. It is produced by the leading suppliers of microcontrollers such Intel, Philips, Siemens, Dallas Semiconductor and Atmel then followed by HC05/HC11 (Motorola), H8 (Hitachi) and 78K (NEC).

The EEC that produced in this research takes RPM signal, crankshaft angle encoder, and an analog voltage from a MAP sensor. Then it processes the data for optimally control the fuel amount relative to engine's operating condition. Those data are also useful to detect the amount of the incoming air. In proportion of the detected incoming air, the EEC will issue an injection-drive (time) instruction to the injector corresponds to the required amount of fuel injection in such a manner that the target A/F ratio may be achieved. A pulse for the injection circuit is resulted defining the duration and timing for fuel injection. The EEC must be capable to adjust those parameters based on engine speed, manifold pressure and tables input by the user. This embedded system is design because of the safety concerns and of the strict constraints on implementation costs. Design and development of every functional block of EEC is described below.

5.3 Main Microcontroller Board Design and Development

The photograph of Figure 5.1 is the main microcontroller board of 89S52 with in system programming (ISP) and power supply. Figure 5.2 is the microcontroller board of 89C51; both of these microcontrollers have been developed. The PCB layout could be drawn using any kind of electronics drawing software such as Protel, P-spice and others. In this case, Protel software is used as a tool. One of the I/O ports of these microcontrollers has been programmed as PWM signal output.

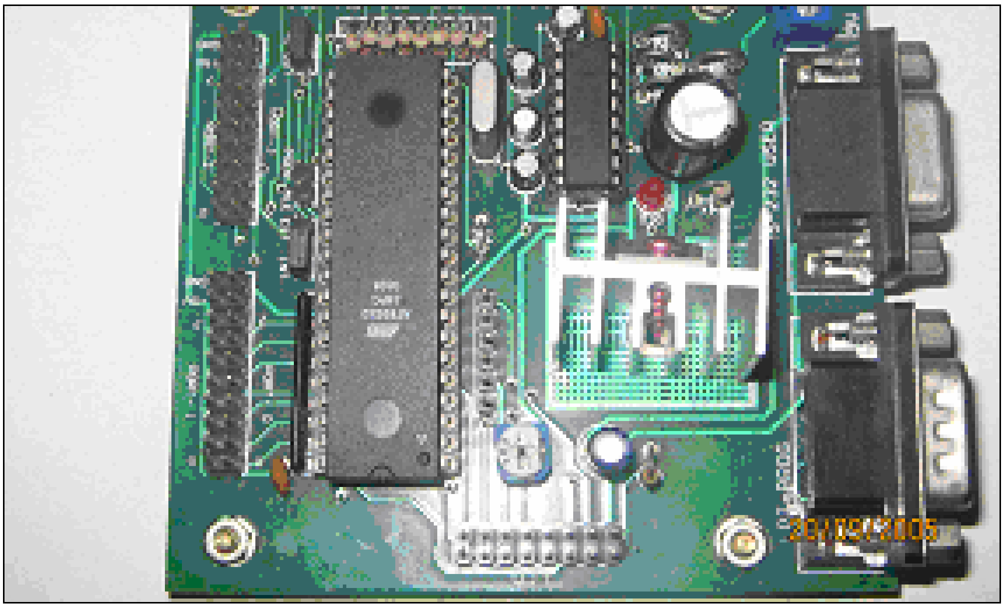


Figure 5.1: Main microcontroller board of 89S52

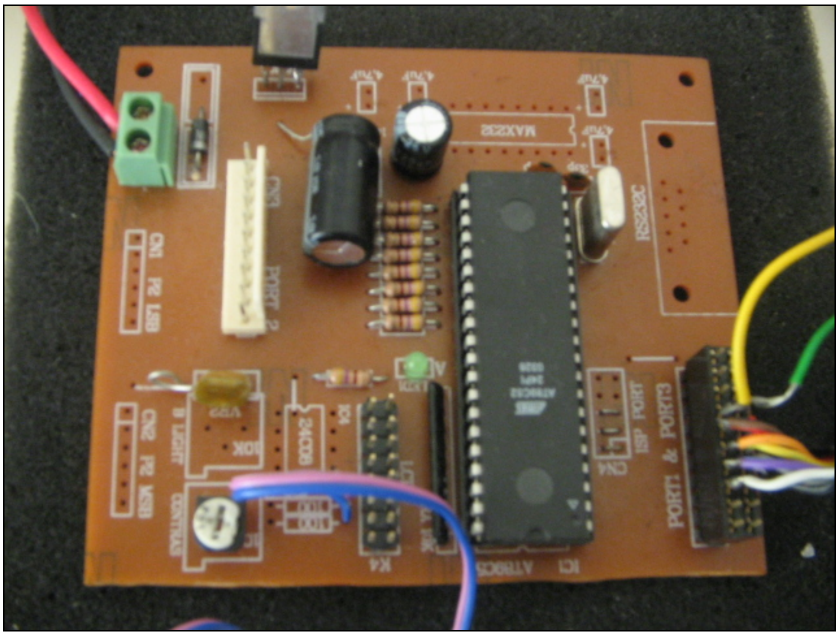


Figure 5.2: Main microcontroller board of 89C51

An external crystal at these microcontrollers provides a timing reference for clocking the CPU. The crystal is 12 MHz that connects to pins 18 and 19 of U_2. This crystal frequency has two advantages. It gives accurate baud rates for serial communications, due to the way that the 89S52 timer divides the system clock to generate the baud rates. The serial communications are reliable if the baud rate is accurate to within a few percent. The higher the crystal frequency, the faster programs will execute. Capacitors C_2 and C_3 are 30 pF each, as specified in the 89S52 data sheet. Their precise value isn't critical. Smaller values decrease the oscillator's start-up time, while larger values increase stability.

These microcontrollers have three 16-bit timer/counters, which are easy to generate periodic signals or count signal transitions. The timers can be used for event counting, where the timer increments on an external trigger and measures the time between triggers. The I/O ports enable to read and write to external memory and other components. These microcontrollers have four 8-bit I/O ports (ports 0-3). Many of the port bits have optional, alternate functions relating to accessing external memory, using the on-chip timer/counters, detecting external interrupts, and handling serial communications.

A 5 V voltage regulator supplies the microcontroller board of AT 89S52. This voltage regulator requires a minimum input voltage range, which is normally 3V higher than the output voltage. Therefore, for this voltage regulator, a constant supply of at least 8V is needed for the system supply to be stable at 5V. For a better system supply, a low dropout type voltage regulator is used so that the output voltage is still stable even the input voltage is decreasing up to 6 V. this phenomena should not be taken for granted because instead of using a battery it is not practical to use an adaptor to be placed on the motorcycle.

This 5 V power supply is needed to power the circuits. Output capability of at least 500 mA is recommended for general experimenting. The power supply can be powered by batteries or AC line voltage, but it must have a regulated output between 4.75 and 5.25 volts. Capacitors C_8-C_{13} provides power-supply decoupling. Capacitors C_9-C_{13} store energy that the components can draw quickly, without causing spikes in the supply or ground lines. C_8 stores energy for quick recharging of C_9-C_{13}. LED_1 and current-limiting resistor R_{10} are an optional power on indicator.

The solenoid requires a very high current, which is more than 1 A. However, the microcontroller could not support this high current. Therefore the interface board is needed to interface the microcontroller and the solenoid valves making use of Darlington pair, battery and a latch. The Darlington pair is used for driving the will drive the solenoid. A diode is connected across the load to protect the transistor (and chip) from damage when the load is switched off. Conduction only occurs when the load is switched off, current tries to continue flowing through the coil and it is harmlessly diverted through the diode.

Since flash memory is integrated on-chip with microcontrollers Atmel AT89C51, its usage became even easier. Having flash memory and a microcontroller on the same chip opened up the opportunity to take advantage of the additional intelligence. An additional ROM area containing code for handling the flash programming is provided. The code does not only provide functions to erase or program the flash memory, it also provides boot code; even with a completely erased flash, the chip can still execute this boot code and accept inputs via the serial port. This code area is not erasable and can be used for recovery of a system. Because of this feature, this code is also referred to as boot loader.

There are two programming methods for flash memory: ISP and in application programming (IAP). ISP allows for re-programming of a flash memory device while it is soldered into the target hardware. However, the application needs to be stopped during the re-programming process. Usually, ISP requires that a service technician manually starts the re-programming procedure by halting the application and setting it into a special boot and/or programming mode. Only after programming is completed, the application can be restarted. In the 89C51, ISP is implemented with the boot loader. The chip is set to ISP mode either by driving pin PSEN high externally right after a hardware reset or by software. When in ISP mode, the 89C51 accepts flash-programming commands via the serial interface.

IAP allows for re-programming of a flash memory device while it is soldered into the target hardware and while the application code is running. With IAP it is possible to implement applications that can be re-programmed remotely without the need of a service technician to actually be present. In general, IAP can always be realized with external flash memory, where microcontroller and memory are separated components. This is true as long as there is some additional code memory available out of which the microcontroller can execute code, while the flash memory is re-programmed. With on-chip flash, IAP is only possible if supported by the microcontroller. The 89C51 parts support IAP also via the boot loader. The application code can call functions in the boot loader area by loading parameters into the registers R_0, R_1 and DPTR and then calling a specific address in the boot loader.

5.4 Speed Microcontroller Design and Development

The speed microcontroller used here is AT89C2051 and detail circuit board provided in Figure 5.3. The AT89C2051 is a low-voltage, high-performance CMOS 8-bit microcomputer with 2 Kbytes of flash programmable and erasable read only memory (PEROM). The device is manufactured using Atmel’s high density nonvolatile memory technology and is compatible with the industry standard MCS-51™ instruction set. By combining a versatile 8-bit CPU with flash on a monolithic chip, the Atmel AT89C2051 is a powerful microcomputer which provides a highly flexible and cost effective solution to many embedded control applications.

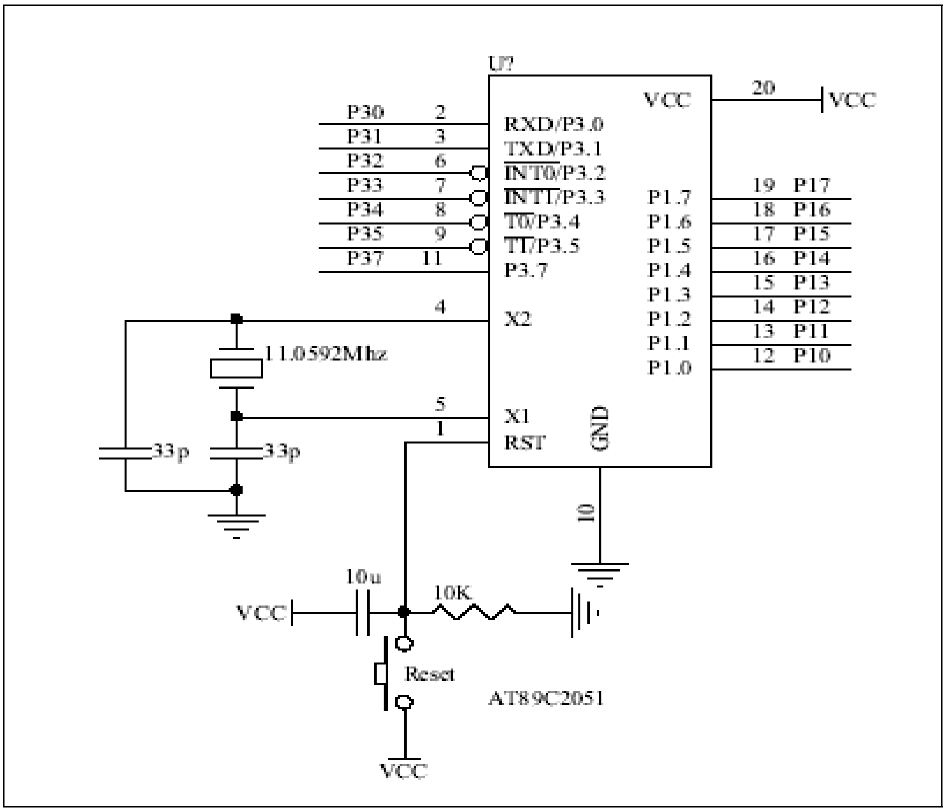


Figure 5.3: Speed microcontroller circuit design

The AT89C2051 provides the following standard features: 128 bytes of RAM, 15 I/O lines, two 16-bit timer/counters, a five vector two-level interrupt architecture, a full duplex serial port, a precision analog comparator, on-chip oscillator and clock circuitry [12]. In addition, the AT89C2051 is designed with static logic for operation down to zero frequency and supports two software selectable power saving modes. The idle mode stops the CPU while allowing the RAM, timer/counters, serial port and interrupt system to continue functioning. The power down mode saves the RAM contents but freezes the oscillator disabling all other chip functions until the next hardware reset. The speed microcontroller prototype is shown in Figure 5.4.

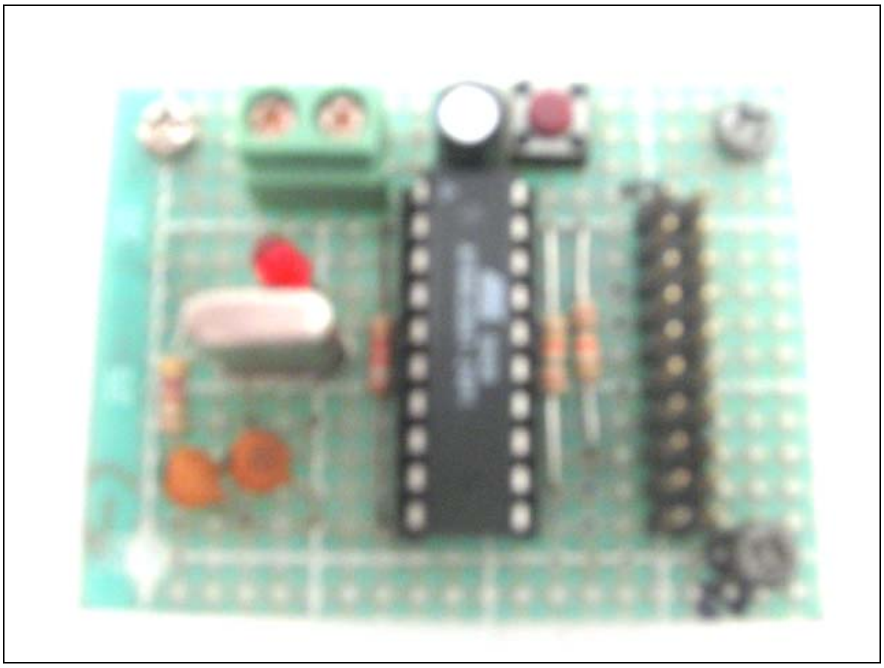


Figure 5.4: Speed microcontroller board of AT89C2051

5.5 A/D Converter Design and Development

The A/D converter used in this EEC design is the ADC0804, CMOS 8-bit. The circuit design is shown in Figure 5. This A/D converter is widely used especially for interfacing with computers. Since this is an 8-bit ADC, the bottom 4 bits are left unused. The converter is configured to automatically clock itself, with a conversion speed governed by R2 and C2 in the circuit.

The ADC 0804 works on the principle of successive approximation that uses a differential potentiometric ladder. It is designed to operate with the 8080A control bus via three-state outputs. These A/Ds appear like memory locations or I/O ports to the microprocessor and no interfacing logic is needed. Differential analog voltage inputs allow increasing the common-mode rejection and offsetting the analog zero input voltage value. In addition, the voltage reference input can be adjusted to allow encoding any smaller analog voltage span to the full 8 bits of resolution.

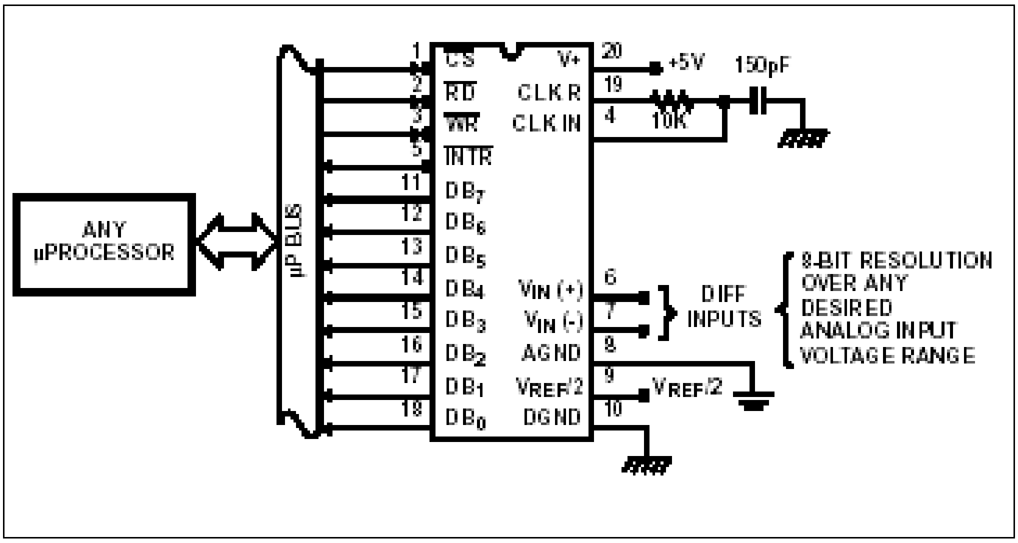


Figure 5.5: ADC0804 circuit design

The simplest in concept and the fastest type of A/D converter is the parallel comparator. This concept is available for microcontroller AT89C2051. The output code from the comparators is not a standard binary code, but it can be converted to any desired code with some simple logic. The major disadvantage of a parallel is the number of comparators needed to produce a result with a reasonable amount of resolution. To produce a converter with N bits of resolution, it needs 2^n–1 comparators. For an 8 bit conversion need 255 comparators. A/D converter 0804 prototype is shown in Figure 5.6.

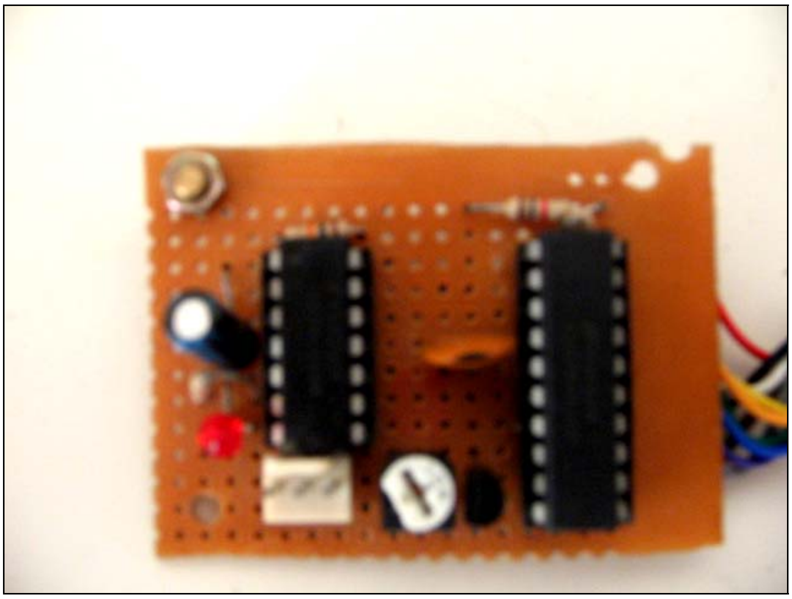


Figure 5.6: ADC0804 board

5.6 Injector Driver Design and Development

The injector driver integrated circuits were designed to be used in conjunction with an external controller. Fuel injectors can usually be modeled by a simple RL circuit. The value of L is 3.98 mH and R is 2.16 Ω, these values were obtained by data sheet provided. The typical values for a performance injector coil are 2 mH and 1 Ω.

The control loop for the injector coil is somewhat similar to the ignition controller, with only some extra things added for the max limit level. The whole idea for the max current limit level and hold current level is to provide performance injectors with the fastest rise time response possible. This is achieved by supplying an initial higher current through the coil, so the solenoid overcomes the initial mechanically resistive force from the helical spring. Once the maximum limit is achieved and the solenoid is fully open, the controller lowers the current through the coil to a suitable holding current limit. This minimizes the power dissipation through the solenoid while holding the solenoid in the state. Both maximum and hold current limits are fully adjustable to suit every coil. The maximum current level break points are from 4A up to 8A with the hold current levels ranging from 1A to 2A.

The LM1949 is chosen as injector driver controller as shown in Figure 5.7. It is linear integrated circuit serves as an excellent control of fuel injector drive circuitry in modern automotive systems.

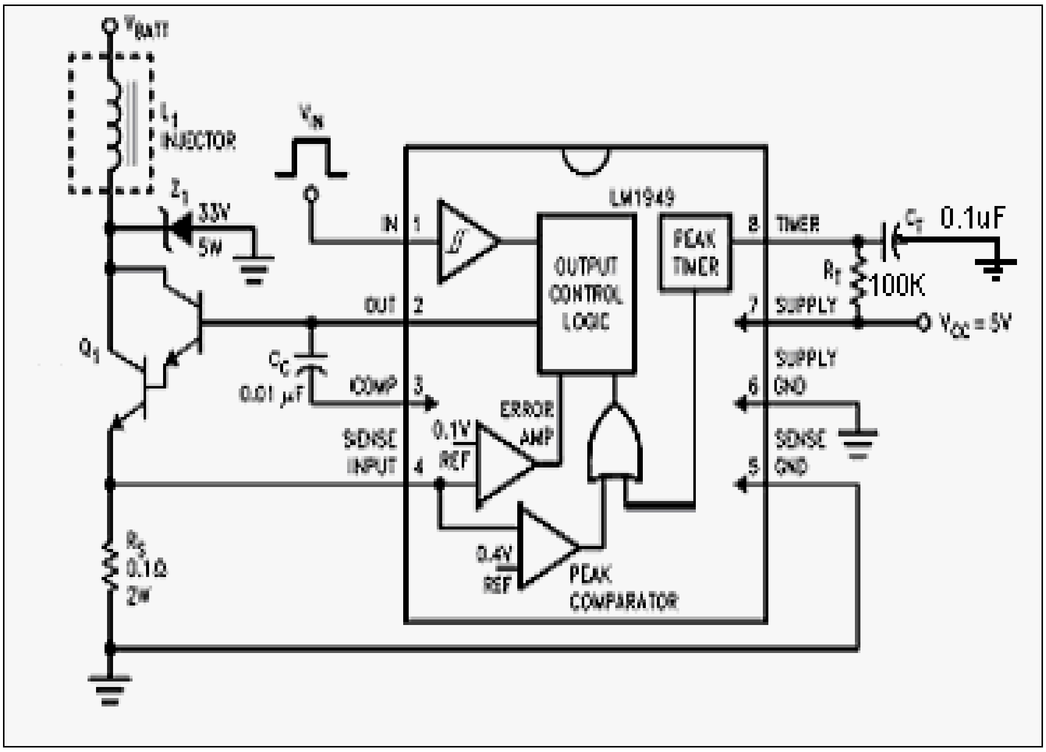


Figure 5.7: Injector drive controller and NPN Darlington

From Figure 5.7, the LM1949 derives its input signal, in the form of a square wave with a variable duty cycle and/or variable frequency, is applied to Pin 1. In a typical system, input frequency is proportional to engine RPM. Duty cycle is proportional to the engine load. In this case, if a single cylinder engine at 10000 rpm, thus the input frequency is given with 166.66 rps. As revolution per second (RPS) is equivalent to frequency (Hertz). The circuits discussed are suitable for use in either open or closed loop systems. In closed loop systems, the engine exhaust is monitored and the A/F mixture is varied (via the duty cycle) to maintain a perfect, or stochiometric, ratio.

The peak and hold currents are determined by the value of the sense resistor R_S of 0.1Ω. This gives peak and hold currents through the solenoid of 3.85 amps and 0.94 amps respectively. This value of R_S of 0.1Ω is chosen in order to guarantee injector operation over the life and temperature range of the system. From data sheet, the injector opens when the current exceeds 1.3 amps and closes when the current falls below 0.3 amps.

The purpose of the timer function is to limit the power dissipated by the injector or solenoid under certain conditions. Specifically, when the battery voltage is low due to engine cranking, or just undercharged, there may not be sufficient voltage available for the injector to achieve the peak current. In order to avoid the injector overheat, the timer function on the IC will force the transition into the hold state after 10 msec. The timer injection system is equal to $R_T C_T$, where the value for R_T is 100 KΩ and C_T is 0.1 μF. The actual range of the timer in injection systems will probably never vary much from the 3.9 milliseconds. However, the actual useful range of the timer extends from milliseconds to seconds, depending on the component values chosen. The timer is reset at the end of each input pulse. The capacitor reset time at the end of each controller pulse is determined by the supply voltage and the capacitor value. The IC resets the capacitor to an initial voltage and peak comparator gives the reference voltage of 0.4 V. Then these voltages are as inputs to the control logic.

Compensation of the error amplifier provides stability for the circuit during the hold state. External compensation (from Pin 2 to Pin 3) allows each design to be tailored for the characteristics of the system and/or type of Darlington power device used. High current should not be allowed to flow through any part of these traces or connections (Pin 4 and Pin 5 respectively). Large currents above one amp, the component leads or printed circuit board may create substantial errors unless appropriate care is taken. An easy solution to this problem on double-sided PC boards (without plated-through holes) is to have the high current trace and sense trace attach to the R_S lead from opposite sides of the board.

The driver IC, when initiated by a logic 1 signal at Pin 1, initially drives Darlington transistor Q_1 into saturation. The injector current will rise exponentially from 0 A to 4.5 A, dependent upon RL circuit of the injector, the battery voltage and the saturation voltage of Q_1. The drop across the sense resistor is created by the solenoid current, and when this drop reaches the peak threshold level, 400 mV, the IC is tripped from the peak state into the hold state. The IC now behaves more as an op amp and drives Q_1 within a closed loop system to maintain the hold reference voltage, typically 94 mV, across R_S. Once the injector current drops from the peak level to the hold level, it remains there for the duration of the input signal at Pin 1.

Since the load is inductive, a voltage spike is produced at the collector of Q1 anytime. This occurs at the peak-to-hold transition, (when the current is reduced to one fourth of its peak value), and also at the end of each input pulse, (when the current is reduced to zero). The zener provides a current path for the inductive kickback, limiting the voltage spike to the zener value and preventing Q1 from damaging voltage levels. Thus, the rated zener voltage at the system peak current must be less than the guaranteed minimum breakdown of Q1. The zener also provides system transient protection. Automotive systems are susceptible to a vast array of voltage transients on the battery line. Though their duration is usually only milliseconds long, Q1 could suffer permanent damage unless buffered by the injector and Z1. There is one reason why a zener is preferred over a clamp diode back to the battery line, the other reason being long decay times. The fuel injector driver board development is shown in Figure 5.8.

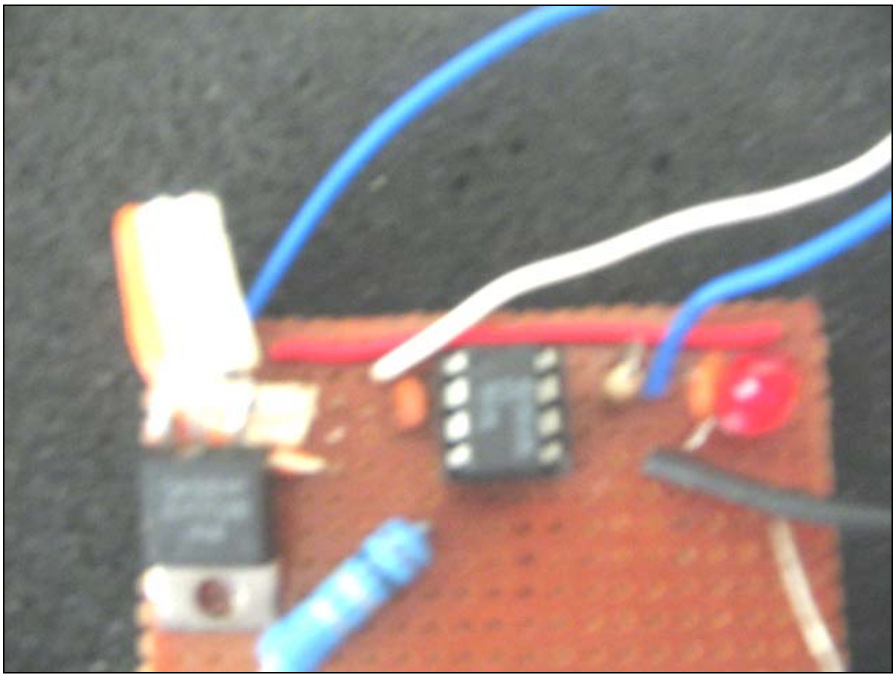


Figure 5.8: Injector driver board

The IC is designed to control an external power NPN Darlington transistor that drives the high current injector solenoid. The current required to open a solenoid is several times greater than the current necessary to merely hold it open; therefore, the LM1949, by directly sensing the actual solenoid current, initially saturates the driver until the “peak” injector current is four times that of the idle or “holding” current. This guarantees opening of the injector. The current is then automatically reduced to the sufficient holding level for the duration of the input pulse.

For Darlington transistor, the power dissipation is important characteristic need to be determined. The power dissipation of the system is dependent upon input frequency and duty cycle of the input waveform to Pin 1. The majority of dissipation occurs during the hold state, and in the peak state nearly all power is stored as energy in the magnetic field of the injector, later to be dumped mostly through the zener.

5.7 Program Development

Software is designed for each engine application to satisfy customer functional specifications. EEC control code is written in a standard modular format, containing replaceable subroutines for each function. Passing of parameters to and from subroutines follows a standard format. Therefore, several control logic strategies are available and customizing involves integrating the desired software modules. Calibration and diagnostic software is embedded within the EEC code to allow passing calibration data from an external PC.

Engine mapping is the process of modeling engine behavior as a function of adjustable engine parameter in terms of RPM and load. The approach of engine mapping currently employed is model-based control with systematic offline design and simulation, rapid control prototyping, and hardware-in-the-loop simulation. These techniques have become well established during the recent years, and have streamlined the development process substantially.

When programming for the embedded system, the processor is working without the aid of an operating system. Some of the things that must be dealt with are the I/O structure, interrupt structure and register set of the system. There are a number of factors that should be considered when choosing between doing programming in assembly or in a high level language like C or C++. Some factors are throughput, memory requirements and availability, development schedules, portability and experience. For a real-time application it is often essential that the services are performed as fast as possible. A program written in assembly language will always be more efficient than a program written in C, but the development time for the assembly code will most likely be longer than that for the C code.

Open loop control system is applied in this research for EEC design and development. Additional program of lookup table is used to enhance its performance as reference data. This program is written by assembly language and stored in microcontroller.

The use of assembly language provides a number of advantages. A program written in assembly language requires considerably less memory and execution time than a program written in a high level language. Assembly language performs highly technical tasks that would be difficult, if not impossible, in a high level language. Knowledge of assembly language provides an understanding of machine architecture that no high level language can ever provide.

Most assemblers provide other features, such as formatting the program code and creating a listing that shows both the machine-code and assembly-language versions of a program side-by-side. The first 256 bytes is the internal RAM size started from 0000H to 00FFH. At address of 1000H, the 64 byte control register block begins. These control registers are very important for the user as a memory area to control the operation of the microcontroller. Any memory locations addressed below 8000H is considered as in the RAM areas. The external I/O device is allocated at 7000H through 7700H, where maximum I/O device that could be used is 64 ports.

5.8 Main Program

An EEC system is designed by reading the input of crank angle, which uses the calculation and the input pulse width to the injector determination methods, after read the rpm and map parameters. This method has successfully done by previous researcher.

The width of pulse for each map and rpm is feed into 3D lookup table. In programming, Appendix B, the pulse width is arranged in a table that enables to modify. This table is put at the end of program and can be accessed by subroutine program.

5.9 Counting Speed

The injection timing by reading the crank angle encoder is calculated from port 3.4 and 3.5. The port 3.4 detects reference 0 to 360 pulse reading from shaft encoder which has been set with resolution of 2 degrees [12]. For engine 4 strokes, one cycle is equivalent to 720 degrees. Thus, this 360 point represents the 720 degree. Map parameter, as analog sensor, is determined by A/D converter 8 connected to port 2 of main microcontroller. Port 1 receives input from speed microcontroller. The speed microcontroller counts pulse in one cycle time then send to the main microcontroller.

Two 16 bits timers/counters in microcontroller AT89C2051, which are controlled by software, are timer/counter 0 and timer/counter 1. These timers are operated at microcontroller frequency of 12 MHz. They count once every 1μs independently, not depend to instruction command. One cycle of time is equivalent to one instruction command. When the time cycle is completed, the timers interrupt microcontroller for information.

If counter input detection is equal to 1, the time is clocked from an external source. In most applications, this external source supplies the timer with a pulse upon the occurrence of an event-the timer is event counting. The number of events is determined in software by reading the timer registers TL_x/TH_x, since the 16 bit value in these registers increments for each event. In counter applications, the timer registers are incremented in response to a 1 to 0 transition at the external input T_x.

The timers are usually initialized once at the beginning of a program to set the correct operating mode. Thereafter, within the body of a program, the timers are started, stopped, flag bits tested and cleared, timer registers read of updated, and so on, as required in the application. The timer mode register (TMOD) is the first register initialized, since it sets the mode of operation. The following instruction initializes timer 1 as a 16 bit timer (mode 1) clocked by the on-chip oscillator (interval timing). MOV TMOD, # 01010010B.

5.10 PWM Output

The easiest way to define pwm is with an interrupt running from one of the timers. Timer is a function of both the pwm frequency and the resolution. The processor is in an endless loop until the timer 0 interrupt occurs. Then it goes off and goes through the timer 0 interrupt routine and returns to the endless loop to wait for the next interrupt. When an interrupt occur the hardware automatically jumps to a predefined location in memory. There is not enough room to actually write an interrupt service routine so the general solution is to put a jump at each interrupt location to the interrupt service routine which can be anywhere later in the program memory.

Duty cycle or time interval is a term used to describe the output pulse. It is given as a percentage. This microcontroller 89C51 operates from a 12 MHz crystal. The shortest possible interval is limited, not by the timer clock frequency but by software. The shortest instruction on the 89C51 is one machine cycle or one microsecond. Time intervals (12 MHz operation) are programmed by 16 bit timer with maximum interval of 65536 microseconds.

5.11 Injector Control Testing

An injector is an electrical-mechanical device that meters and atomizes fuel. From this definition, the diagnostic procedure injector performance test can be done either mechanically or electrically.

In electrical procedure, this is a two-part analysis. One is the electrical integrity of the injector and the other is the computer's ability to provide a pulse to the injector at the proper time. At one time, a resistance check of the injector was all that was done to confirm its electrical ability. This test seemed to be adequate and some techs still use it, but a one-time check of an injector's resistance is not always enough. This is due to the fact that resistance will change with an injector's temperature. Thousands of injectors pass a resistance test at room temperature and fail when heat was added.

Many techs use a noid light to prove a signal from the EEC. This test shows nothing about supply voltage or injector pulse width. Today the digital storage oscilloscope (DSO) is a common tool. Many technicians look at an injector's voltage pattern to confirm supply voltage and good ground, inductive kick when the injector is turned off and a measurement of pulse width. Others use a low amp current probe with their DSO as the preferred method of obtaining a waveform. This allows the tech to confirm the EEC signal, injector pulse width, and injector circuit current usage. DSO patterns can also be helpful in diagnosing mechanical operation by showing the pintle hitting its opening and closing points.

For mechanical procedures, at one time a stethoscope might have been used to listen for a clicking noise coming from an injector. Many times, unless injectors were being pulsed individually, the vibration of one injector could be carried through the rail and heard at another injector. The injector waveform can provide this information with the observation of pintle bumps.

Variables that can be monitored and functions to determine mass of fuel injected during steady state or acceleration are mass flow of intake air, intake manifold air pressure, and intake manifold air temperature. Intake manifold air temperature is assumed a constant; this is due to no variation in temperature during experimental test. While the mass flow air intake can be replaced by MAP.

There is very little configuration for the MAP sensor even though it is arguably the most important sensor in the system. The manifold pressure is simple enough to be implemented in an 8 bit micro-controller. Vehicle implementation requires minimal numerical calculations and the time derivatives of noisy sensors are not necessary. The MAP is less complicated than many of the transient-fuel compensation algorithms currently in production vehicles. Engine control systems that currently use the speed density method for estimating air flow rate may be easily adapted to the MAP to estimate air flow rate at the throttle to help achieve transient air-fuel control similar to that of a fast air-mass sensor although steady state accuracy is still comparable to traditional speed-density. Table "look-ups" are used to minimize real-time execution.

Taking into account the fact that the flame spread takes time, ignition and injection has to start well before TDC point (advance). The minimum advance for best torque is determined by the engineers using dynamometer. Camshaft detection and crank shaft tooth detection determine the engine rpm and thus update time events. The engine was operated satisfactorily air control mode.

5.12 Conclusions

The Electronic Fuel Injector Controller (EFIC) was successfully developed. It was designed as a compact unit and installed directly to the engine. It contains a printed circuit board (PCB) with electronic components. The CPU with onboard RAM and ROM will minimize the interface components. Pulse width modulation (PWM) for the fuel injector is done by a timer which has been programmed to control the output pulse width.

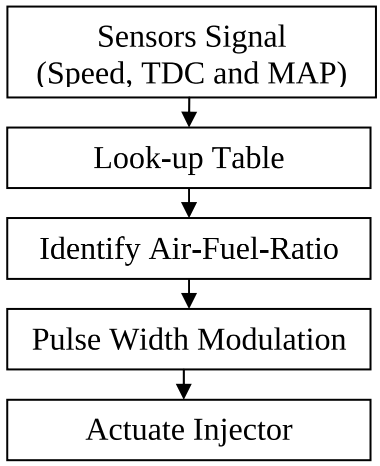


Figure 5.9: EFIC Flowchart

A multi terminal plug connects the EFIC to its sensors, injector, as well as to its power supply. The EFIC must withstand high temperature, humidity and physical stresses. The input signals for this EFIC is the engine speed, top dead center (TDC) marking and manifold absolute pressure (MAP). The MAP will be calibrated with the air-fuel-ratio (AFR) through experimental results.

The calibration process is done by performing thorough engine testing. The results then will be used as in a look-up table which will be programmed within the EFIC. Through sensors input, the best AFR will then be defined and correct mass of fuel will be injected to the combustion chamber. The amount of fuel injected will be control by PWM (output of the EFIC) which actuate the injector solenoid.

Chapter 6

DIRECT FUEL INJECTION SYSTEM

6.1 Introduction

The application of gasoline direct-injection (GDI) in a two-stroke engine is more challenging than in four-stroke engine. In general, two-stroke engine has power stroke on every cycle, which means fuel needs to be injected in every cycle. This particular nature limits the injection period to 360° CA unlike 720° CA as in four-stroke engine. To solve the fuel "short-circuiting" problem during scavenging process, adequate fuel needs to be injected when all ports are closed. This prerequisite sets further constraint to the atomization process within two-stroke GDI engines.

The development of a prototype GDI atomizer for the compound-piston engine is an aspiration to solve the fuel "short-circuiting" problem while introducing many performance enhancement possibilities. A cross-section of the compound-piston engine attached with the proposed GDI atomizer is shown in Figure 6.1. For the engine specified above, a prototype GDI atomizer conceptual design was developed by considering seven important specification areas as shown in Figure 6.1. A cross-section of the compound-piston engine attached with the proposed GDI atomizer is shown in Figure 6.2.

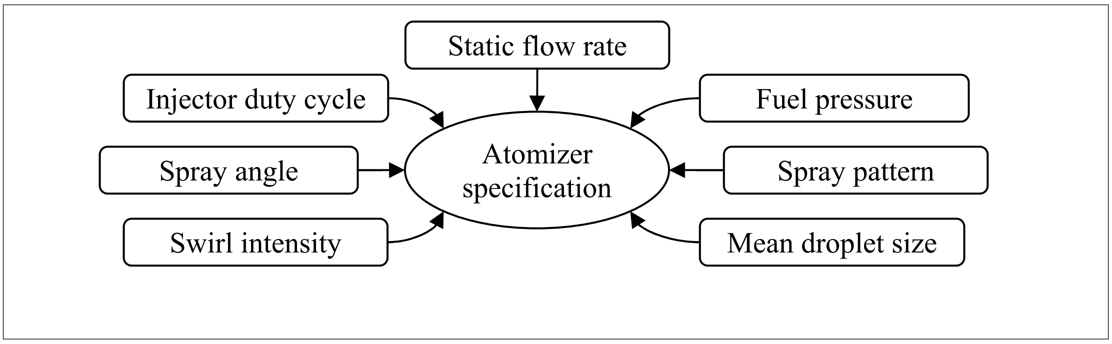


Figure 6.1: Seven important areas that constitute to an ideal pressure-swirl Injector

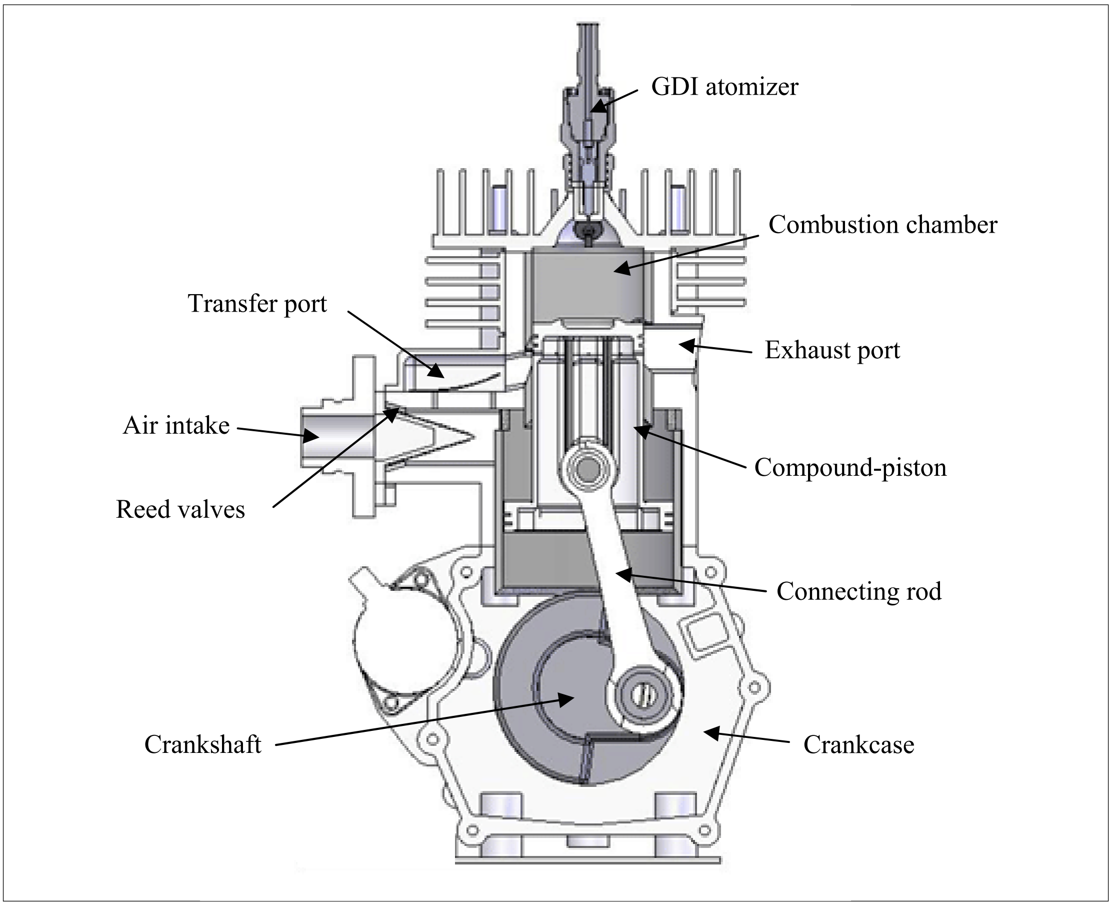


Figure 6.2: Cross-section of the stepped-piston engine with the fitting of the prototype GDI atomizer.

6.2 System Description

Figure 6.3 show the schematic layout of the overall fuel injection system developed for the prototype engine. This is a dedicated direct fuel-injection system developed as a mean of further improving the engine operational efficiency and is very much in line with the trend of small engine development program i.e. incorporating an effective fuel dispensing system.

Here the fuel is pressurized by an axial-type mechanical pump, which is driven via the engine crankshaft. A pressure relief valve is attached to the high-pressure fuel line to maintain the fuel pressure at 5.0 MPa while excessive fuel is returned back to gasoline tank. To reduce the fluctuation of the fuel pressure, a small fuel accumulator is also attached to the high-pressure fuel line. The fuel injector used is a prototype pressure-swirl injector with a static flow rate of 480 cc/min rated at 5.0 MPa. The spray produced by this type of injector is a hollow-cone and its nominal spray half-cone angle is 32°. The injector is driven by the control module located in the Electronic Fuel Injector Controller (EFIC). Connected to the EFIC are i) speed sensor, ii) crank angle sensor, and iii) manifold absolute pressure (MAP). These sensors serve as input parameter for the EFIC to determine the correct injection timing and pulse width at any speeds.

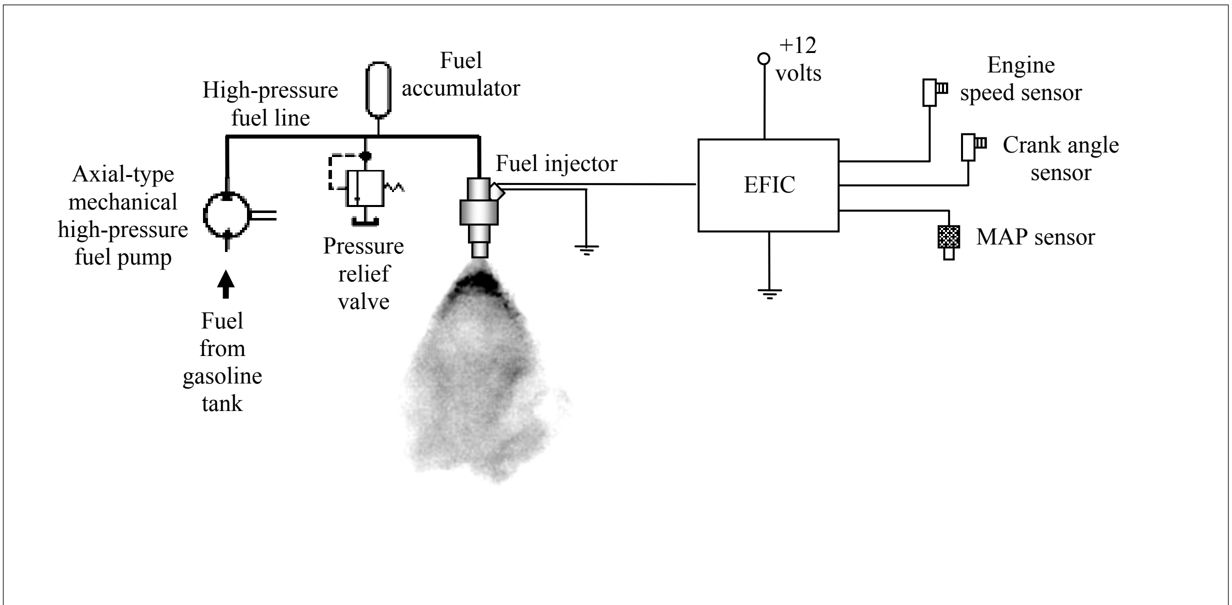


Figure 6.3: Schematic layout of the indigenously developed direct fuel-injection system

6.3 GDI Conceptual Design

Figure 6.4 shows an exploded view of the injector mark O conceptual design. The design consists of eight main components altogether. To realize the concept, only five components were freshly designed to complete the prototype injector assembly. The five components are: (i) nozzle, (ii) swirler, (iii) body, (iv) lock and (v) needle. Another two components i.e. Spring and Solenoid were scavenged from a used stock *Mitsubishi* GDI injector. The o-rings used in this prototype are Buna-N type, which has excellent resistance to petroleum-based oils and fuels. They are readily available as standard parts.

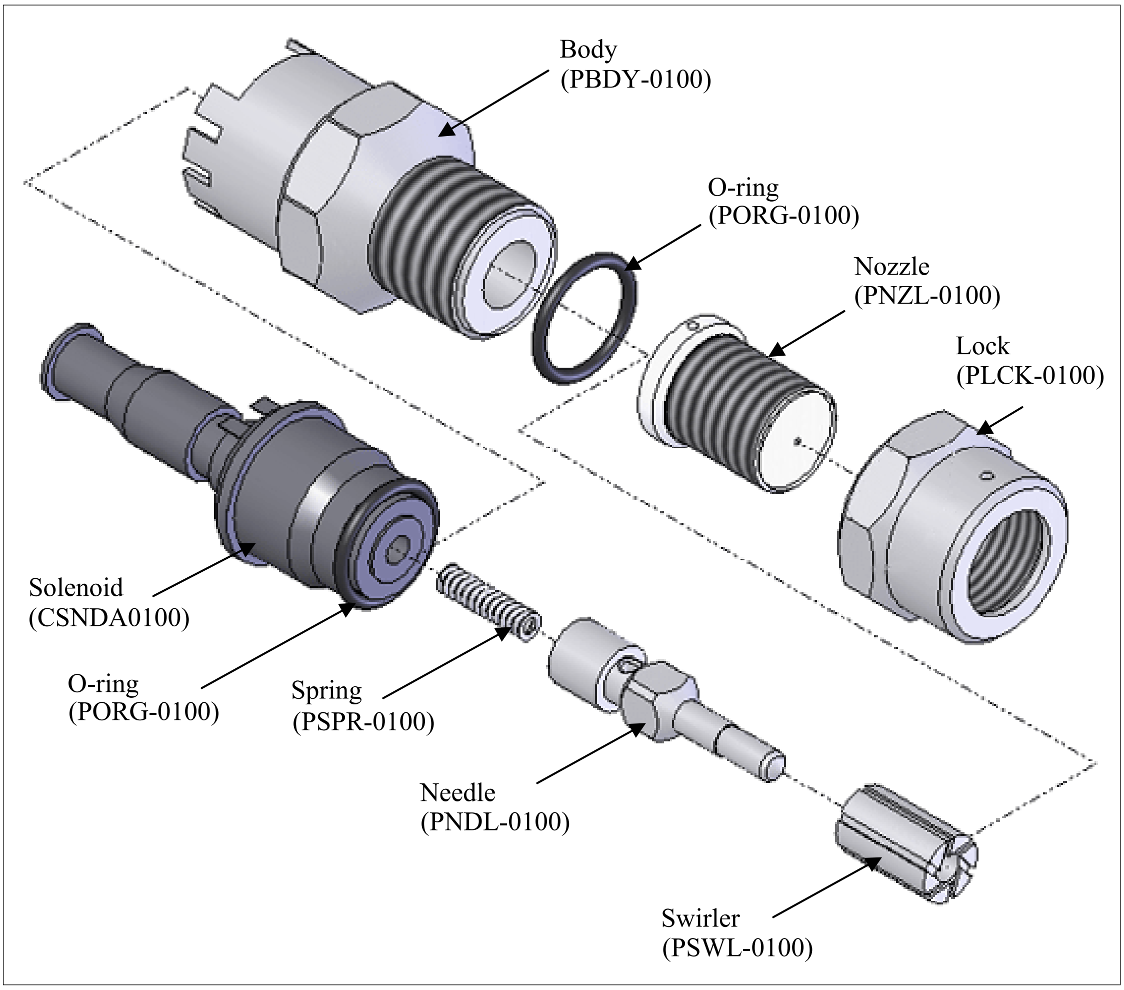


Figure 6.4: Exploded isometric view of prototype injector mark O (CINJ-0100)

6.3.1 The Nozzle

The nozzle of the injector (PNZL-0100) was intended to have a single final orifice for fuel dispersion. Determining the size of the final orifice is critical because it affects two important requirement contradictions:

1. the orifice diameter must be big enough so that it has sufficient flow rate to deliver rich fuel during full load engine operation

2. the orifice diameter must be small enough to able better atomization of fuel droplet design

The final orifice of the nozzle was designed to have a diameter of 0.76 mm due to the following rationale:

- At the specified pressure, the static flow rate of the injector should be about 454.38 cc/min (at fuel-ambient pressure differential of 5.0 MPa) to satisfy the stoichiometric engine requirement up to 10,000 RPM
- The droplet SMD exiting the final orifice should be less than 20 μm when 5.0 MPa fuel line pressure is applied
- A good pressure-swirl atomizer typically has a low discharge coefficient, C_D lower than 0.3
- By estimating C_D value between 0.10 and 0.20, and by referring to Figure 10.5, choosing the diameter of the nozzle orifice of 0.76 mm should satisfy both droplet size and static flow rate requirements

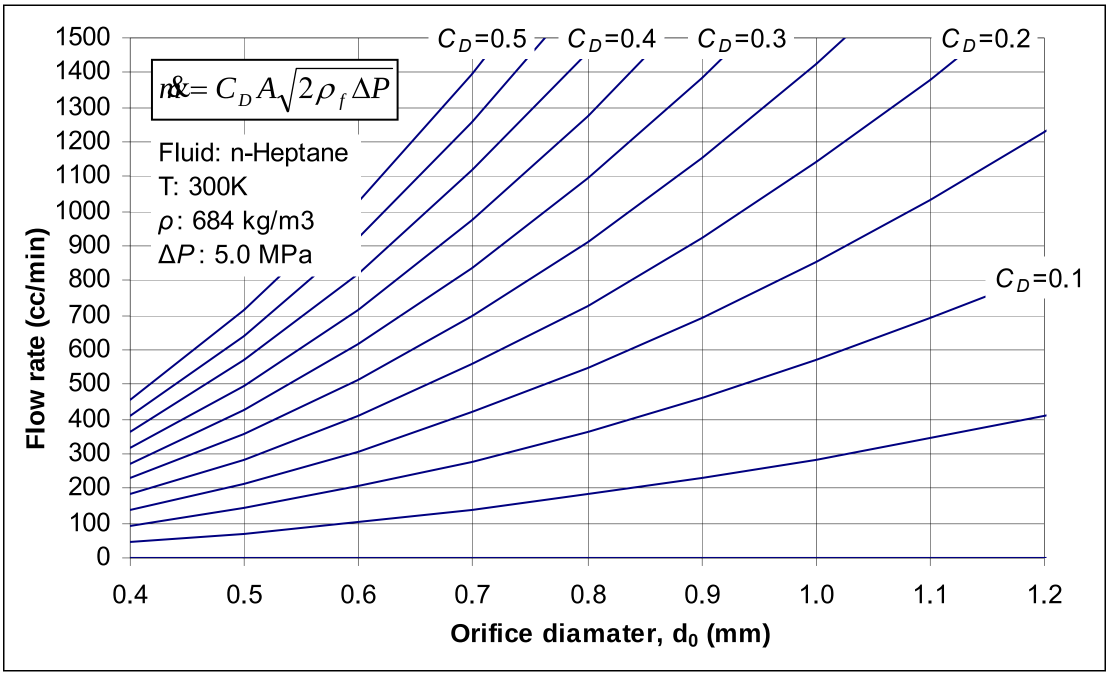


Figure 6.5: Mapping of correlation between nozzle orifice diameter and static flow rate with a given discharge coefficient C_D.

At this stage, since both static flow rate and droplet diameter are further influence by discharge coefficient, C_D and vice versa, only estimation value of C_D can be provided using CFD Eulerian multiphase calculation. Actual C_D for the prototype injector had to be determined from static flow rate test after the prototype fabrication.

The material chosen for the PNZL-0100 is 60 HRC hardened *ASSAB* XW-42 steel. The *ASSAB* XW-42 is a high-carbon, high-chromium tool steel alloyed with molybdenum and vanadium. Such material is recommended for application requiring very high wear resistance.

6.3.2 The Swirler

When the Swirler is assembled with the Nozzle, a cavity formed takes the shape of six tangential swirl slots. The tangential swirl slots function as a pathway to force a swirling motion of the fuel flowing through the final orifice. The higher number of the slots, the more uniform the resultant swirl velocity is. On the other hand, the strength of the swirl velocity is controlled by the angle of the tangential slots perpendicular to the axial axis of the Swirler.

The initial conceptual swirler (PSWL-0100) bears six symmetrical tangential slots slanted about 60° to its axial axis. Apart from that, the Swirler also acts as a guide for the Needle reciprocating movement. The hole of the Swirler should have sufficient fit to guide the needle from tilting while the clearance should allow attachment of a thin layer of fuel for adequate lubrication. The Swirler was made from 55 HRC hardened *ASSAB* DF-3 steel. The *ASSAB* DF-3 is a medium-carbon steel alloyed with manganese, chromium and tungsten to give a good combination of surface hardness and toughness after hardening. Its hardness should provide enough wear resistance against the Needle reciprocating movement.

6.3.3 The Needle

The Needle or plunger has to reciprocate in order to produce cyclic fuel supply for the combustion. The final orifice is normally closed during non-operating state by action of a compressed helical spring. During operation, the needle is lifted by means of electromagnetic force to allow fuel flow through the final orifice via needle seat passage. The lift distance of the needle which has a typical value of less than 100 μm, has to be controlled so that the fuel dispersion has a proper value of C_D as discussed earlier.

The researchers have conducted an investigation that leads to a conclusion that the end-point shape of the needle has considerable effect on the atomization of the liquid fuel. By numerical analysis, it was shown that under similar operating condition, sharp-pointed needle promotes better atomization that round-end needle. Thus, the end-point of this prototype injector was purposely designed to be sharp-pointed.

The shape of the Needle (PNDL-0100) was designed to allow smooth fuel flow. In addition, the shape should provide minimal contact against the needle guide (PSWL-0100) to assist efficient needle reciprocating movement. A 55 HRC hardened DF-3 carbon steel was chosen as its material because of its excellent performance against wear as well as its high relative magnetic permeability to act as armature.

6.3.4 The Body and the Lock

The Body of this injector (PBDY-0100) was designed to allow the stock solenoid (CSNDA0100) to mate flexibly with other injector parts. The Lock (PLCK-0100) function is to hold together the whole assembly while allowing easy access for modification or maintenance of the Spring, Needle, Swirler and Nozzle. The material selected for both parts is 316 stainless steel. The 316 stainless steels are austenitic, or nonmagnetic, alloyed with chromium and nickel for enhanced surface quality, formability and increased corrosion and wear resistance (AK Steel, 2000). Besides that, it is also known to have good elevated temperature strength.

6.4 Prototype Fabrication and Assembly

Altogether, there are five items fabricated. The whole process of machining, hardening and finishing were done by a precision machining vendor. It took about one month to complete. Upon received, all the items physical dimensions were rechecked. There are however some out-of-tolerance at certain areas, but in some non-critical areas, several exceptions were made. Necessary assemblies were done, and the finished products are shown in Figure 6.6 till 6.11.

Figure 6.6: Injector assembly (CINJ-0100) + wire harness + o-ring

Figure 6.7: Injector assembly (CINJ-0100)

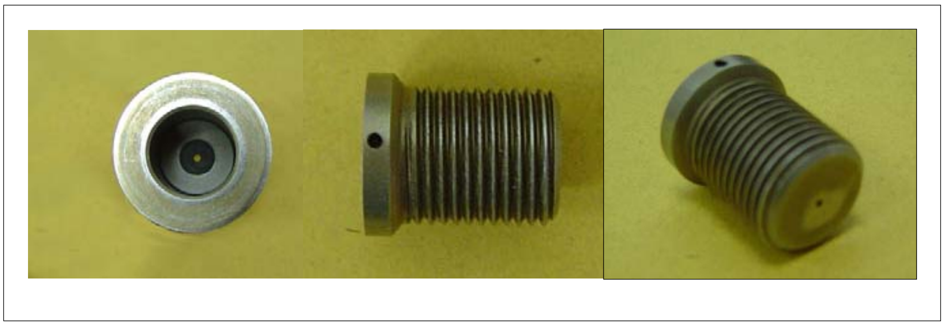


Figure 6.8: Nozzle (PNZL-0100)

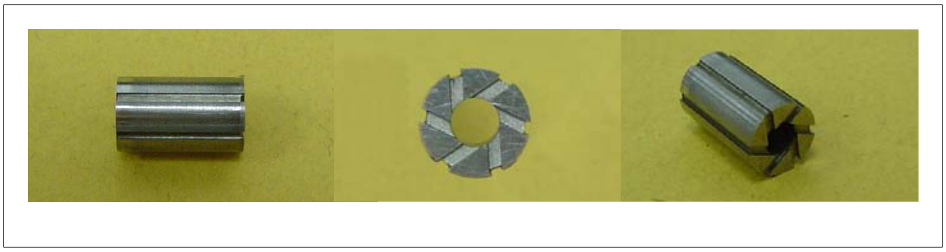


Figure 6.9: Swirler (PSWL-0100)

Figure 6.10: (Left) Needle (PNDL-0100), sub-assembly of Nozzle + Swirler

Figure 6.11: (Left) sub-assembly of injector Body (CBDY-0100) + Solenoid (CSNDA0100), and Lock (PLCK-0100)

6.5 Leak Test

Seat leakage may cause incorrect fuel metering, loss of fuel line pressure, and abnormal formation of deposit at the injector orifice. Incorrect fuel metering may result in leaner or richer AFR which may cause high percentage of exhaust emission level. Loss of fuel pressure may increase the time required to achieve desired rail pressure thus may result larger mean droplet size. In consequence it may lead to increased cranking time, rough idles, stalls, and/or a no-start condition (SAEJ1832, 2001).

SAEJ1832 (2001) proposes the use of dry nitrogen as a test medium for leakage test. However, a similar but simpler approach was chosen for this study. The prototype injector was connected to an air compressor that supplies pressurized air of 0.7 MPa. Any air leakages were detected by spraying soap water onto the injector body and nozzle. Body leakage problem was solved accordingly, while seat leakage problem was rectified by grinding or polishing the needle valve against its valve seat.

6.6 Prototype Development

Although necessary steps are taken to ensure a quality product during the conceptual design stages and manufacturing, the fabricated product slightly differs from its theoretical design. The discrepancies were caused by manufacturing tolerance that is subjected to the precision machining accuracy and repeatability. However, design problems seemed to be the main factor for prototype evolution. The prototype injector had to undergo six major stages before it actually complied with the specification requirements outlined earlier. Each stage was marked with roman numerals I-VI. Each mark signified a major change in either part or sub-assembly of the prototype injector.

The part changes involved in each mark is shown in Table 6.1. Relevant evolutions are highlighted in bold faces. During the whole prototype evolution, only four types of part or sub-assembly were improved.

Table 6.1: Evolution of prototype injector components

Prototype Mark	BDY	LCK	NDL	NZL	ORG	SND	SPR	SWL
O	01	01	**01**	01	01	01	01	01
I	01	01	**02**	01	01	01	01	01
II	01	01	**03**	01	01	**01**	01	01
III	01	01	03	01	01	**02**	01	01
IV	01	01	03	01	01	**03**	01	**01**
V	01	01	03	**01**	01	03	01	**02**
VI	01	01	03	**02**	01	03	01	02

Table 6.2: Improvements and weaknesses of prototype injector mark O - VI

Prototype Mark	Changes	Improvements made	Main weaknesses
O	-	-	• No Injection
I	Needle 01 → 02	• Weak injection	• Injection limited at ΔP <0.4 MPa • Needle magnetism • Intermittent spray performance
II	Needle 02 → 03	• Injection at higher ΔP <0.8 MPa • No needle magnetism	• Injection limited at ΔP <0.8 MPa • Intermittent spray performance
III	Solenoid 01 → 02	• Injection at higher ΔP <2.8 MPa	• Injection limited at ΔP <2.8 MPa • Intermittent spray performance
IV	Solenoid 02 → 03	• Injection at higher ΔP <3.5 MPa	• Coarse spray droplet • High static flow rate • Intermittent spray performance • Small half spray cone angle (~15°) • Unsymmetrical spray pattern
V	Swirler 01 → 02	• Lower static flow rate (524 cc/min) • Finer spray droplet but not fully atomized • Consistent spray performance • Larger spray cone angle (~25°)	• Coarse spray droplet • Static flow rate too high for 125 cc cylinder • Unsymmetrical spray pattern
VI	Nozzle 01 → 02	• Lower static flow rate (116 cc/min) • Fully atomized spray • Symmetrical spray pattern	–

They are: (i) Needle (NDL), (ii) Nozzle (NZL), (iii) Solenoid (SND), and (iv) Swirler (SWL). During the evolution, each root cause of the weaknesses of each prototype mark was identified. Then, improvements were made accordingly. All the corrective actions made in all six evolution stages are summarized in Table 6.2.

6.6.1 Needle

The biggest problem with the freshly fabricated prototype (mark O) was there was no injection. Upon post-mortem, the root cause was pinpointed towards the poorly designed Needle (CNDL-0100). Besides its bulky shape, and relatively heavy weight, the CNDL-0100 also has a large surface contact area with other parts, which resisted its movement. In addition, after acting as an armature (electromagnetically energized by the injector coil), the whole CNDL-0100 became permanently magnetized. This magnetism behavior prevented further needle movement as it was strongly stuck to the ferritic Swirler (PSWL-0100) and Nozzle (PNZL-0100).

As a countermeasure, a new needle (CNDL-0200) was designed with slender-looking shape, lighter weight, less surface contact area, and a novel material configuration. The CNDL-0200 consisted of two parts: Needle A (PNDLA0100) and Needle B (PNDLB0100). The PNDLA0100 was made of *ASSAB* XW-42 while PNDLB0100 was made of *ASSAB* DF-3. A lower composition of ferrite in *ASSAB* XW-42 was believed to lower the magnetic permeability of PNDLA0100, hence help solving the magnetism problem. As a result, the prototype injector (mark I) was able to perform fuel injection. However, the injection pressure was only limited up to ΔP = 0.4 MPa, and the needle magnetism problem still persist.

Another decision was made to produce another needle (CNDL-0300). This time, the material for Needle A (PNDLA0200) was changed to 316 stainless steel. The 316 stainless steel is austenitic or non-magnetic. Although it has some composition of chromium and nickel to enhance wear resistance, it cannot be hardened by heat-treating. The Needle B (PNDLB0200) still uses the same material but its length was increased to facilitate its function as an armature for the solenoid coil. Additionally, more holes were drilled into PNDLA0200 to help the fuel flow while to reduce the total weight of the needle CNDL-0300. Consequently, relatively higher injection pressure was achieved and the needle magnetism problem was solved.

All three needles are illustrated in Figure 6.12. A comparison of their material and weight is summarized in Table 6.3 along with a needle from stock *Mitsubishi* GDI injector.

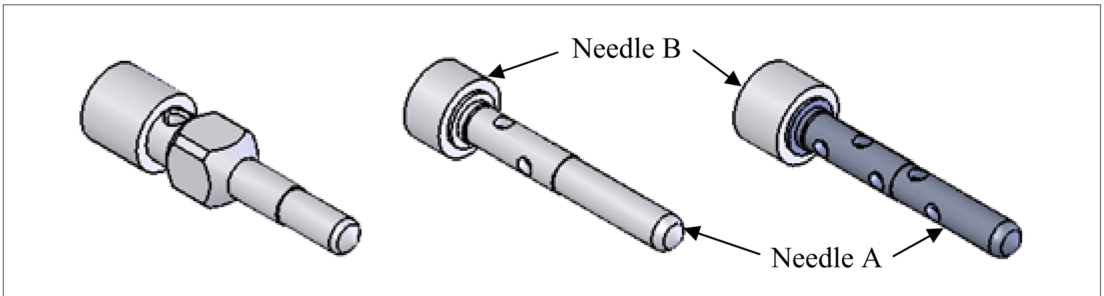


Figure 6.12: (Left to right) CNDL-0100, CNDL-0200, and CNDL-0300

Table 6.3: A comparison of needle material and weight

Needle	*Mitsubishi* GDI	CNDL-0100	CNDL-0200	CNDL-0300
A	-	-	(XW-42) 3.16	(316SS) 2.65
B	-	-	(DF3) 1.62	(DF3) 2.08
Total weight (g)	2.86	(DF3) 8.14	4.78	4.73

6.6.2 Solenoid

From several test done, it was found that the scavenged solenoid from a used stock *Mitsubishi* GDI injector (PSNDA0100) was unable to perform up to par with the prototype injector. Using PSNDA0100, the prototype injector was only able to perform with liquid fuel pressure up to 0.8 MPa. Thus, an effort was made to build a second solenoid (solenoid B), which wraps the stock PSNDA0100 around the injector outer body (PBDY-0100).

For this purpose, the PBDY-0100 was modified to reduce its outer diameter. Figure 6.13 showed the illustration of the PBDY-0100 before and after modification (PBDY-0101). The outer diameter cut was deemed necessary to produce a solenoid coil with smallest diameter possible, which would result in a stronger magnetic field generation.

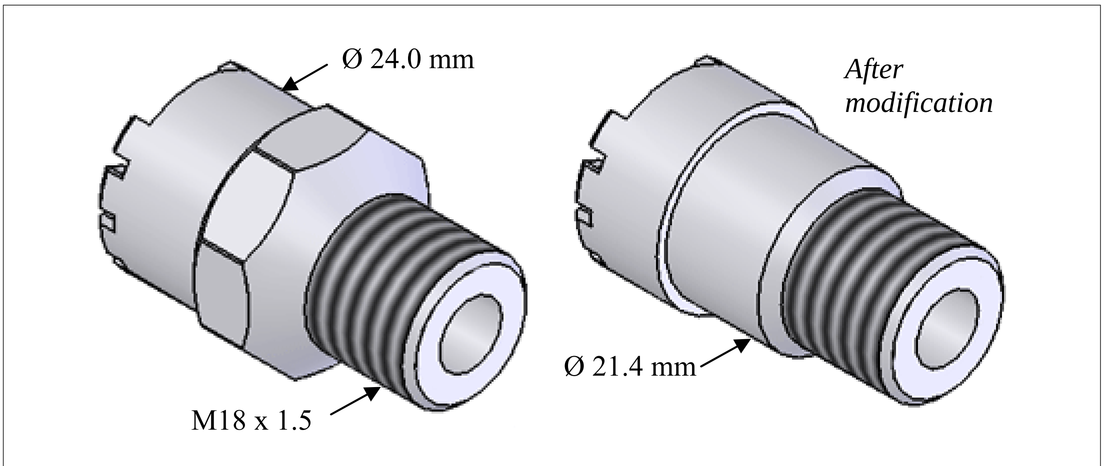


Figure 6.13: (Left) PBDY-0100 and PBDY-0101

The first solenoid B (CSNDB0100) was designed using 0.37 mm diameter annealed copper wire. It comprises of 309 turns with the ability to produce a maximum magneto-motive force of 862 ampere-turns (AT). However, when it was tested, it can only be operated up to fuel line pressure of 2.8 MPa. Thus, another attempt was made to produce a relatively stronger solenoid B (CSNDB0200). This time, it uses 0.70 mm diameter annealed copper wire with only 150 turns to generate a higher maximum magneto-motive force of

3175 AT. From the calculation, the coil characteristics for both solenoids B are summarized in Table 6.4.

Table 6.4: Calculated specification of solenoid B

Coil Characteristics	CSNDB0100	CSNDB0200
Wire diameter, d_w (mm)	0.37	0.70
Wire cross-section area, A_w (mm^2)	0.0963	0.3850
No. of turns, N_w (Turns)	309	150
Resistance, R (Ω)	4.3	0.6
Current, I (A) (V=12 volts)	2.8	21.2
Magnetomotive force, $N_w I$ (AT)	862	3175
Magnetic field, B (mTesla)	45.2	153.3
Magnetomotive force density, $N_w I / A_c$ (AT/mm2)	29.0	55.1
Power dissipated, $I^2 R$ (Watts)	33.5	254.0

6.6.3 Injector Driver Circuit Upgrade

Upon the test performed using the prototype injector mark IV (with CSND-0300), the injector driver circuit made by Abdullah (2003) ceased to function. It was found that the Darlington transistor BDX53C used to drive the injector coil was shorted. The BDX53C is an NPN power transistor mounted in TO-220 plastic package with a maximum rated collector current of 8 A. The damage was caused by the much lower injector coil impedance, which allowed a high current flowing through the collector that exceeds the BDX53C maximum rating.

To rectify the problem, the Darlington transistor BDX53C was substituted by a BDW42. The BDW42 is also an NPN power transistor mounted in TO-220 plastic package. However, the BDW42 possessed higher maximum ratings than the former. A simple comparison between BDX53C and BDW42 is presented in Table 6.5.

Table 6.5: A maximum ratings comparison between Darlington transistor BDX53C and BDW42 (STMicroelectronics, 1999; ON Semiconductor, 2002)

Parameter	BDX53C	BDW42
Collector-Emitter Voltage, V_{CEO} (volts)	100	80
Collector current, I_C (A)	8	15
Total power dissipation, P_D (Watts)	60	85
Collector-Emitter Saturation Voltage, $V_{CE(sat)}$ (volts)	3	3

Besides the Darlington transistor upgrade, the driver circuit was also modified. Two 100 Ω resistors in parallel were attached to the transistor base, and a 4.7k Ω resistor was connected between base and emitter. These additional resistors were to ensure collector-emitter voltage saturation. In addition, two 5W low impedance cement resistors were added to the collector to smoothen the driver voltage pulse spike. A circuit diagram for both driver circuits are shown in Figure 6.14.

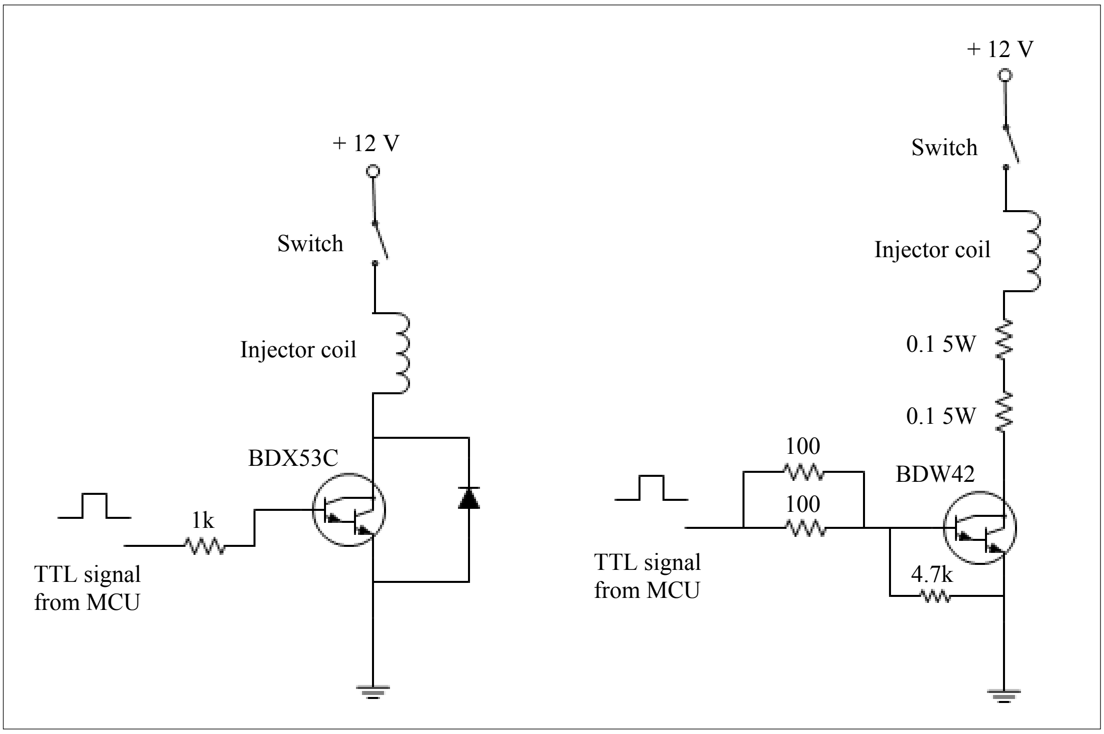


Figure 6.14: Original injector driver circuit, and upgraded driver circuit

6.6.4 Swirler

A new swirler (PSWL-0200) was redesigned based on the first (PSWL-0100) to resolve a few distinctive problems:

1. Coarse spray droplet
2. High static flow rate
3. Small half spray cone angle (~15°)
4. Unsymmetrical spray pattern
5. Intermittent spray performance

The first two problems were rectified by reducing the size of the tangential slots hence the total inlet port area. The third problem was addressed by increasing the swirl intensity via escalating the tangency of the swirl slots. The fourth problem was countered by mounting the number of the slots from six to eight. The last problem was caused by improper needle guidance. As it reciprocates, the needle wobbles too much causing it to miss its tight designated valve seat. As a resort, the length of the needle guide was made longer while the gap between the needle and the (swirler) needle guide was optimized. On top of these, the side slots were also redesigned to facilitate uniform and smoother flow while improving the PSWL-0200 manufacturing process cost. Both swirlers are illustrated in Figure 6.15.

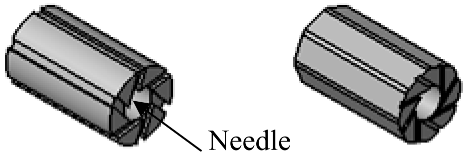


Figure 6.15: (Left) PSWL-0100 and PSWL-0200

6.6.5 Nozzle

Although the application of swirler PSWL-0200 managed to lower the prototype injector static flow rate, the flow rate is still too much for a 125 cc cylinder. In addition, there are still visibly some traces of unsymmetrical spray pattern observed. Thus, a new nozzle (PNZL-0200) was made to replace the original PNZL-0100. Both nozzles are shown in Figure 10.16. They may look very much alike, because they possessed (almost) similar geometrical characteristics as well as the built material. But the fact is, they actually differed in terms of final orifice length, l_0 and diameter, d_0. The PNZL-0100 has a d_0 = 0.76 mm, while PNZL-0200 has a d_0 = 0.40 mm. The ratio of l_0/d_0 for PNZL-0100 is 3.62 while for PNZL-0200 is 2.50.

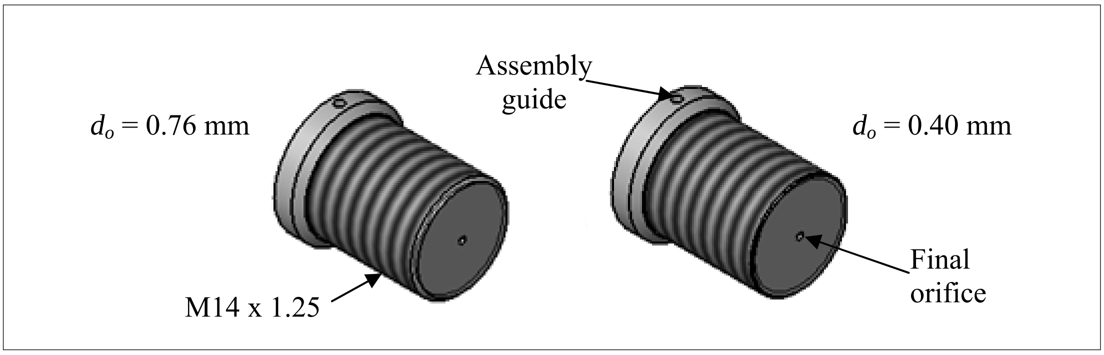


Figure 6.16: (Left) PNZL-0100 and PNZL-0200

By reducing the l_0 / d_0 ratio it was found that the droplet SMD diminished continuously over the range of l_0 / d_0 from 2.82 to 0.40. On the other hand it was presumed that l_0 / d_0 of less than 0.40 would gain further improvement in atomization quality. Nevertheless, such value may not be suitable in GDI application where the nozzle is subjected to high fuel pressure and cyclic high-pressure high-temperature combustion. Furthermore, conceptual nozzles designed with l_0 / d_0 ratio of less than 1.0 intended for GDI failed several finite element analysis (FEA) tests during design evaluation stages. However, the FEA tests carried out were out of the scope of this study.

6.7 Final Design

A working prototype injector (mark VI) and its cross-section is illustrated in Figure 6.17. A photograph of the complete product (with wire harness) is shown in Figure 6.18.

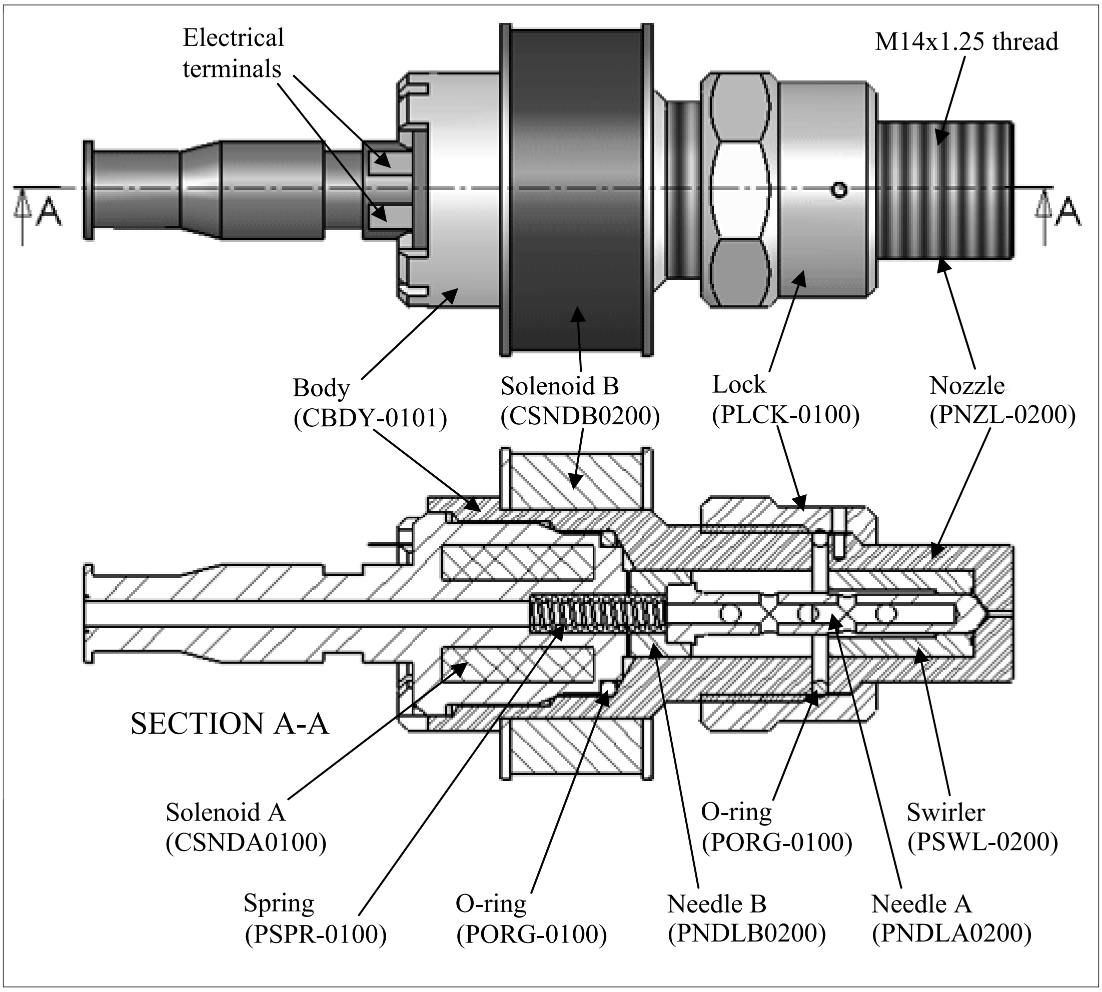


Figure 6.17: Schematic of injector mark VI (CINJ-0600)

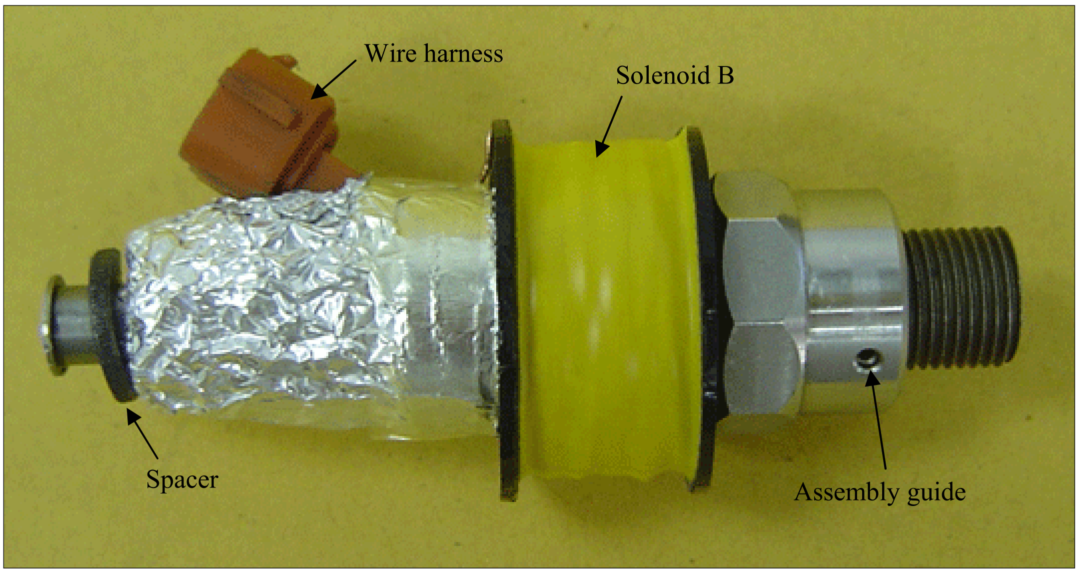


Figure 6.18: Working prototype injector mark VI (CINJ-0600)

6.8 Special Features

The injector was designed to include the following distinctive features of flexibility:

- The nozzle should be easily fitted into spark plug of hole size M14 x 1.25
- Interchangeable spring, needle, swirler and nozzle
- Accessible modification of response time, needle lift, swirl strength and flow rate to optimize atomization and for other engine requirement

A novel idea that came along with this development is to be able to produce a prototype injector with the ability to suit any GDI engines with modest parts modification. In order to control the injection parameters, several injector parts were identified. A generalized control strategy is summarized in Table 6.6.

Table 6.6: Flexible control strategy for the prototype injector

Injection Parameter	Control Parts	Required Modification
Response time	Spring, needle, solenoid	Spring strength, needle weight, solenoid electromagnetic field strength
Swirl strength	Swirler	Swirler tangential slot angle
Swirl uniformity	Swirler	Swirler tangential slot quantity
Flow rate	Nozzle	Orifice diameter and discharge coefficient
Droplet size	Needle, swirler, nozzle	Needle shape, swirler tangential slot angle, nozzle orifice diameter, discharge coefficient, and etc.
Spray angle	Swirler, nozzle	Swirler tangential slot angle, nozzle orifice diameter and length
Spray penetration	Swirler, nozzle	Swirler tangential slot angle, nozzle orifice diameter and length

With all the features listed above, the prototype GDI atomizer should also perform its basic functional requirements. In summary, a gasoline direct injector for the specified engine should possess general specifications shown in Table 6.7.

Table 6.7: Conceptual injector specification for a 125 cc two-stroke gasoline engine

Duty cycle	20% (during compression)
Static flow rate	455 cc/min at 5.0 MPa
Half cone angle	30° (±3°)
Mean droplet size	17 micron SMD (approx)
Fuel pressure	5.0 MPa
Spray pattern	Symmetrical hollow-cone

6.9 Specification Test

The prototype injector was subjected to specification test that is consisting of static flow rate, and discharge coefficient test. The static flow rate test and the discharge coefficient test were performed in compliance with SAEJ1832 (2001) using an injector test rig made by Abdullah, one of the member of the research group. The static flow rate of the prototype injector was measured at a rated fuel pressure of 0.3 MPa. The injector static flow rate will then be used as a guideline in controlling the AFR at any engine-operating map.

The static flow rate test was performed to obtain the prototype injector static flow rate specification at a given fuel pressure. During this test, the fuel injector dynamic flow at a rated pressure for a given pulse width (PW) was measured. From the dynamic flow data, the static flow rate, Q_S of the injector was determined. The rated value of the injector static flow rate will be used as a guideline in controlling the fuel injected at a specific engine-operating map by designating a correct PW.

The list of apparatus for this test is given in Table 6.8, the schematic diagram is presented in Figure 10.19 and the photograph of the test rig is shown in Figure 10.20. This experiment utilized a custom-made injector controller developed by Abdullah (2003). The heart of the injector controller is a *Motorola* MC68HC811E2 microcontroller with 16-bit timer, 8 channel 8-bit A/D, and 2k EEPROM. The microcontroller unit (MCU) EEPROM was programmed using assembler language. The start of injection and the duration of injection program were written into the EEPROM before any experiment begins. The test procedure to measure injector static flow rate at low pressure of 0.3 MPa was adapted from SAEJ1832 (2001).

Table 6.8: List of apparatus for static flow rate test

No.	Part name	Specification	Part No.	Serial No.
1	*Warlbro* (in-tank) Fuel Pump	Supply: 12V Rated: 225lph at 3 bar	GSS341 10003-1	5421306
2	Pressure relief valve	Max pressure: 10 MPa	–	–
3	Test injectors		–	–
4	Custom-made injector controller	Injection timing and pulse width can be controlled by programming 68HC11 microcontroller	–	–
5	*Tektronix* digital oscilloscope with 10x voltage probe	60 MHz; 1G Samples/second	TDS-210; Tek P6139A	B106320
6	Measuring beaker	Capacity: 25ml Readability: 1ml	–	–
7	*Shimadzu* electronic balance	Capacity: 2,200g Readability: 0.01g	BL-2200H	D421502496
8	Mercury thermometer	Range: -10~110°C Readability: 0.5°C	–	–
9	Fuel tubes and connectors	SAE standard	–	–

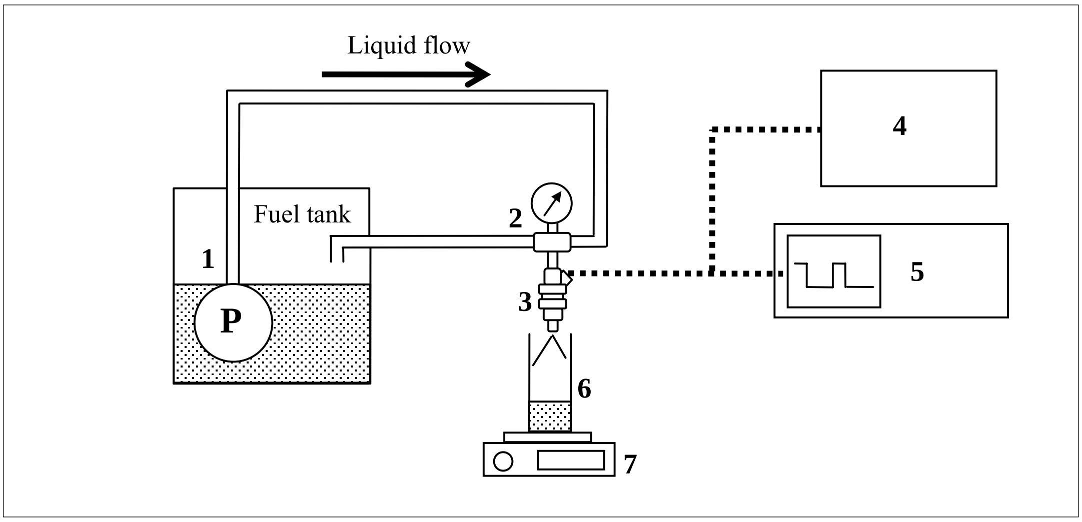


Figure 6.19: Schematic apparatus setup for static flow rate test

Although SAEJ1832 (2001) advice the use of n-Heptane as a standard test fluid, premium unleaded gasoline was used in this study subjected to its availability. However, gasoline is volatile and tends to evaporate even at room temperature. Thus, to maintain the test fluid properties, gasoline collected from the sprays were never reused again. In other words, the test was performed using only fresh premium gasoline.

Referring to Figure 6.19, the liquid fuel was pressurized by in-tank electric fuel pump (1). The fuel pressure was regulated at 0.3 MPa by pressure relief valve (2). The MCU EEPROM in the injector controller (4) was programmed with injection period fixed at 10 ms/pulse. To warm up the system, the injector PW was set to 5 ms (or 50% duty cycle), and then was activated for at least 5,000 pulses. The weight of the fuel injected for 5,000 pulses were collected using beaker (6) and was measured using electronic balance (7).

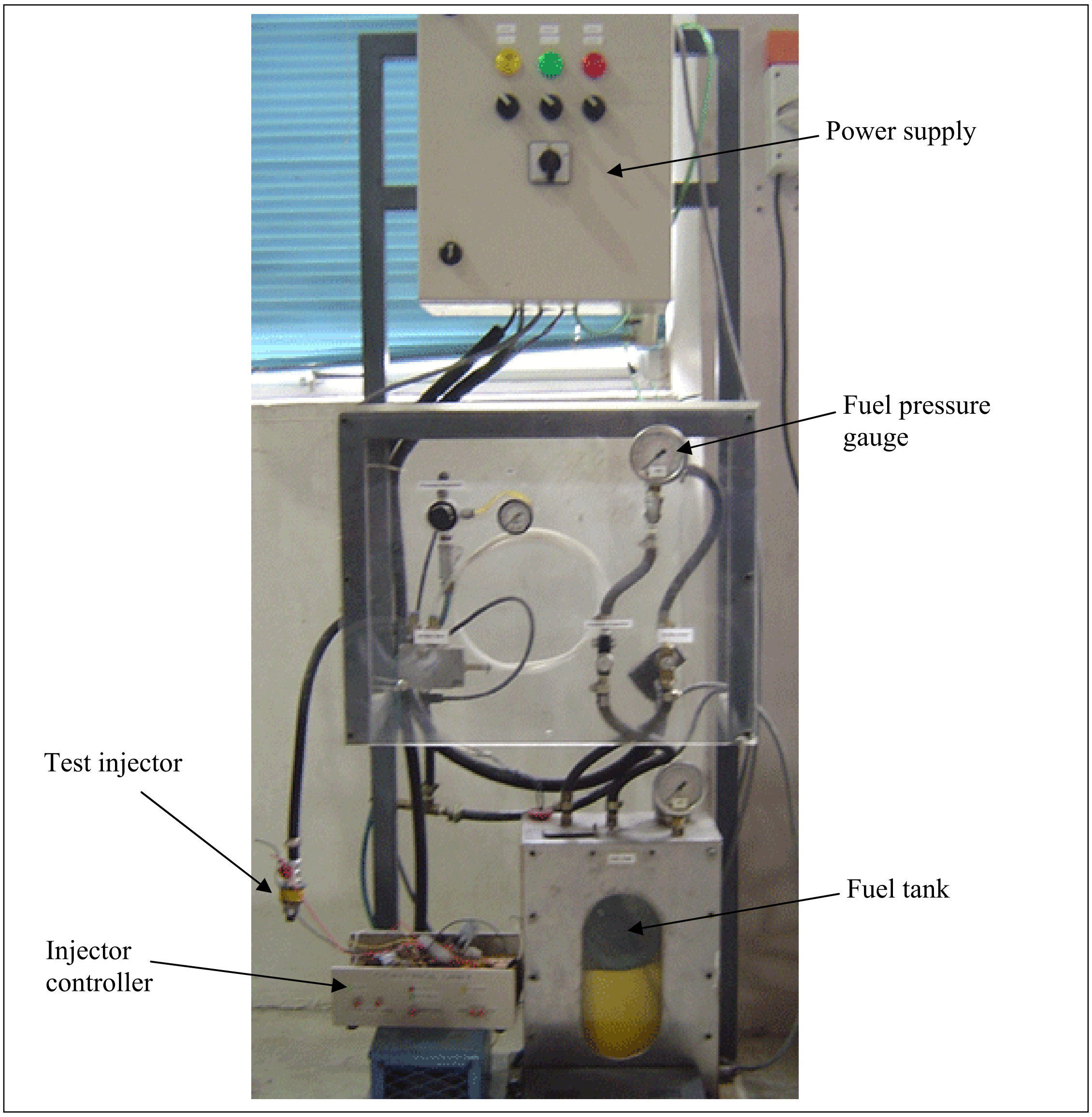


Figure 6.20: Photograph of the static flow test rig

The procedure was repeated for each PW of 1, 2, 3, 4, 5, 6, 7, and 8 ms/pulse. The PW and the injection period signaled to the injector were affirmed using a digital oscilloscope (5). From the measurements, a graph of fuel dynamic flow, Q_d (mg/pulse) versus injector pulse width, PW (ms/pulse) was plotted.

6.10 Spray Performance Test

The purpose of the spray performance test is to measure initial spray angles, and mean droplet sizes of the spray generated by the tested injector at several designated fuel pressure. The measurement was done using high-speed photography technique using a CCD camera. The purpose of the camera was to capture the spatial volume of the spray at an instant after start of injection (SOI). The camera was placed at right angles to a Nd:YAG laser sheet, which provide the instantaneous illumination to “freeze” the spray evolution process. From the photograph captured, the initial spray angle, and the mean droplet size were measured.

Table 6.9: List of apparatus for performance test

No.	Part name	Specification	Part No.	Serial No.
1	Electric motor (of *Hartridge* Diesel Fuel Pump Tester)	Input: 3-phase 415 V Output: 5,000 RPM	HA 875 Type 04 ANS	712-1119
2	*Yanmar* axial-type fuel pump	Flow rate: (see Appendix C)	–	–
3	Fuel tank	Capacity: 5 liters	–	–
4	High-pressure fuel pipe	Cut steel pipe complying with SAEJ1418 (2002)	–	–
5	*Bosch-Rexroth* accumulator	Type: diaphragm type Operating pressure: adjustable (by fill up N_2 gas) Volume: 16.4 cc	–	–
6	*Swagelok* pressure gauge	Range: 0-6 MPa Readability: 0.2 MPa	EN 837-1	–
7	Custom-made common rail	–	–	–
8	*Swagelok* pressure relief valve and fuel return	Operating pressure: adjustable (by spring tightening) Max: 10.0 MPa	–	–
9	Custom-made injector controller	Injection timing and pulse width can be controlled by programming 68HC11 microcontroller	–	–
10	*Tektronix* digital oscilloscope with 10x voltage probe	60 MHz; 1G Samples/second	TDS-210; Tek P6139A	B106320
11	Test injectors	–	–	–
12	Closed transparent glass cylinder	Diameter: 150 mm Height: 500 mm	–	–

13	*New Wave* Nd:YAG laser source	Rate: 15 Hz Pulse duration: 5-10 ns Energy: 10-400 mJ per pulse	Solo III	16337
14	*Flow Sense* high-speed camera	Type: CCD Data transfer: 2M, 8 bit	9080C0831	186
15	*FlowManager* PIV software	–	–	–
16	*Dantec Dynamics* PIV control hub	–	9080N0601	226
17	Portable media	–	–	–
18	*Oxford Lasers* VisiSize Solo software	Function: Mean droplet diameter calculation from TIFF images	2.018	–
19	Tap	–	–	–
20	Filter container	–	–	–
21	Sponge filter	–	–	–

The list of apparatus for this test is given in Table 6.9. The test was conducted using setup as shown in Figure 6.21. A photograph of the test rig is shown in Figure 6.22. The test injector was mounted vertically downwards to eliminate the gravitational influence on spray geometry. The laser illumination was set to slice the center of the symmetrical spray in the axial plane relative to the test injector. The lens of the CCD camera was set tangent to the plane of the laser sheet to capture spatial samples of the spray characteristics. Since there is only one high-speed CCD camera available, the results were further limited to 2-D. Moreover, due to limitation of apparatus, only spatial droplet samples could be captured.

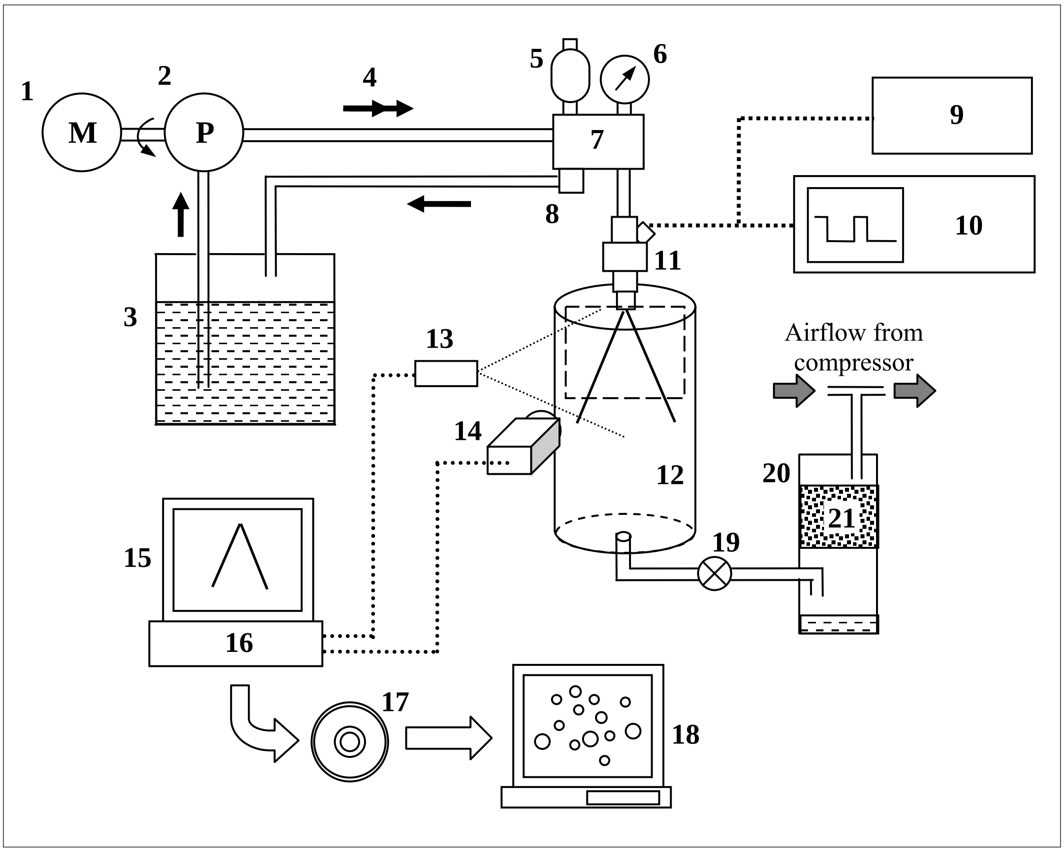


Figure 6.21: Schematic apparatus setup for spray performance test

6.11 Basic Operation

The basic operation of the test rig shown in Figure 6.21 is described as follows: Electric motor (1) cranks high-pressure fuel pump (2). Fuel accumulator (5) and common rail (7) accumulates fuel from fuel tank (3). Pressure relief valve (8) return excess fuel when fuel pressure in the common rail (7) exceeds regulated pressure shown in pressure gauge (6). Injector controller (9) was preset earlier energizes the test injector (11) for a certain duration.

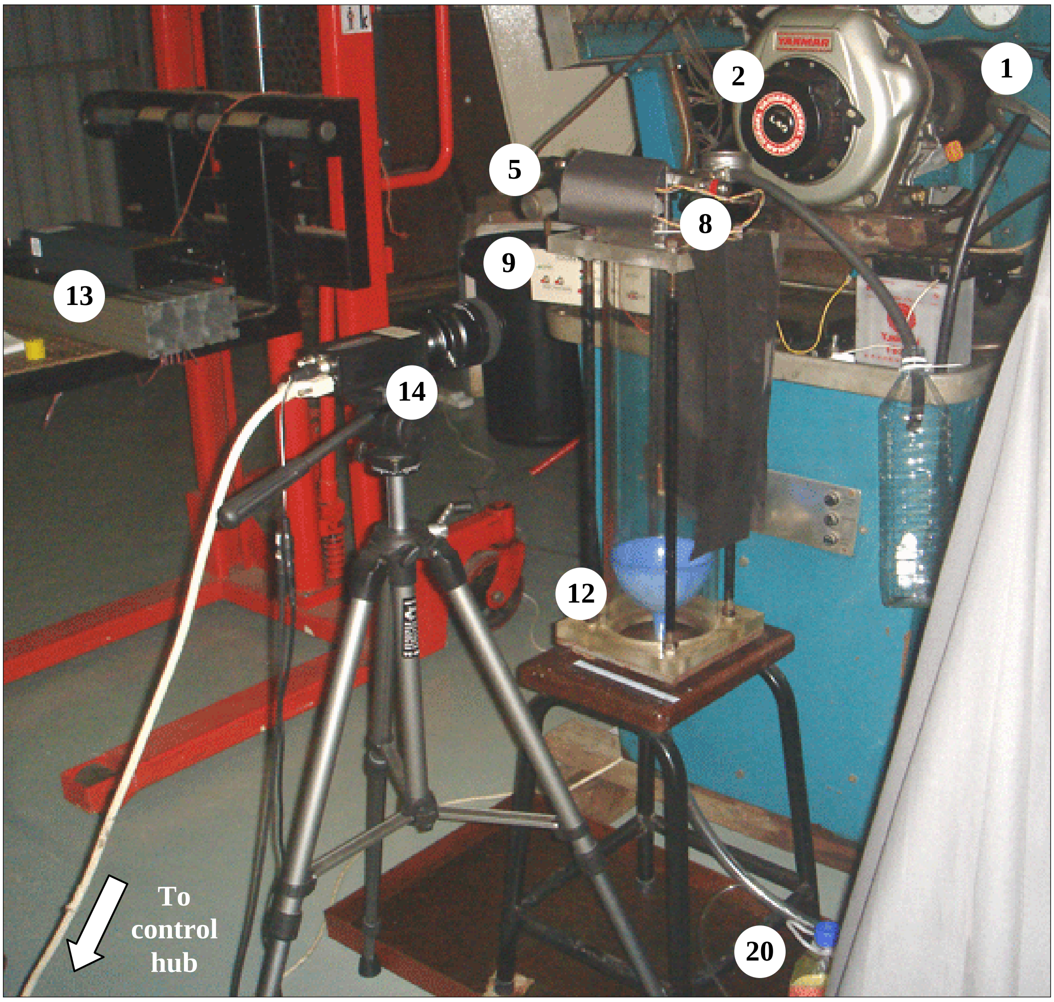


Figure 6.22: Part of the dedicated spray performance test rig

The fuel was sprayed into a transparent glass cylinder (12), which functions to maintain a quiescent ambient. A few milliseconds after start of injection, a laser source (13) illuminate the spray by forming a thin light sheet in an axial plane. A high-speed camera (14), which was placed tangent to the laser sheet, instantaneously captures the spray image. PIV system controller (15) controls both the laser illumination and image capturing process. PIV software (16) stores the image for further analysis of velocities and spray angles.

Another set of spray images were transferred to another computer via a removable drive (17). A droplet sizing software (18) was used to calculate the mean droplet size from the sampled images. After each spray, tap (19) was opened to empty the mixture inside the glass cylinder (12). The mixture was vacuumed through a filter container (20). A sponge filter (21) was used to trap the mixture from escaping into the environment.

6.12 Auxiliary Components of the GDI System

There are seven major components that made up the direct-fuel injection system for the engine. There further explain in the following sub-sections.

6.12.1 Axial-type High Pressure Pump

Since market-available electrical fuel pumps cannot operate at pressure of more than 1.0 MPa, a mechanical fuel pump was used instead. The mechanical fuel pump used in the experiment is taken from a *Yanmar* 200 cc direct-injection diesel engine. The axial type pump can supply fuel at pressure up to 10.0 MPa. Since the pump was designed for diesel fuel, its application using gasoline is anticipated to cause minor hitch such as lack of fuel lubricity. The lack of fuel lubricity will enhance the wear of the fuel pump, which in time will lead to leakage.

6.12.2 Fuel Accumulator

The fuel accumulator in used is a *Bosch-Rexroth* diaphragm-type accumulator. The accumulator consists of part fluid, part gas, with a diaphragm as separating element. When the fuel pressure rises, the gas is compressed. When the pressure falls, the compressed gas expands and forces the accumulated fuel into the line.

Before commissioning the accumulator it must be charged the specified pressure such that the gas pressure should be at approximately 90% of the minimum operating pressure. The gas used to charge the accumulator is 99.99 vol. % of nitrogen gas.

The accumulator has volume storage of 0.075 liter and a maximum pressure of 250 bar, that is ample for a single cylinder application. The diaphragm is made of Buna-N type rubber (NBR) which is suitable for unleaded gasoline of temperature between -10 and +40°C.

Figure 6.23: Accumulator cross-sectional view [13]

6.12.3 Engine Speed Sensor

The engine speed sensor uses the same sensor as the crankshaft angle sensor. If the sensor detects a hole, the output will generate a high pulse (+5 volt). In order to obtain the current engine speed, the ECU counts the total number of pulses detected by the speed sensor for every one second. To get the engine speed in RPM, the following formula will be used:

$$\text{Engine Speed} = \text{total number of pulses per second} \times (60 / 72) \qquad (6.\ 1)$$

The ECU starts activating the one-second timer and counting pulses when the Zero TDC sensor detects the zero TDC position. When the one- second timer stops, the ECU has counted the total pulses. By applying Equation 6.1, the RPM engine speed can be obtained.

6.12.4 Crank Angle Sensor

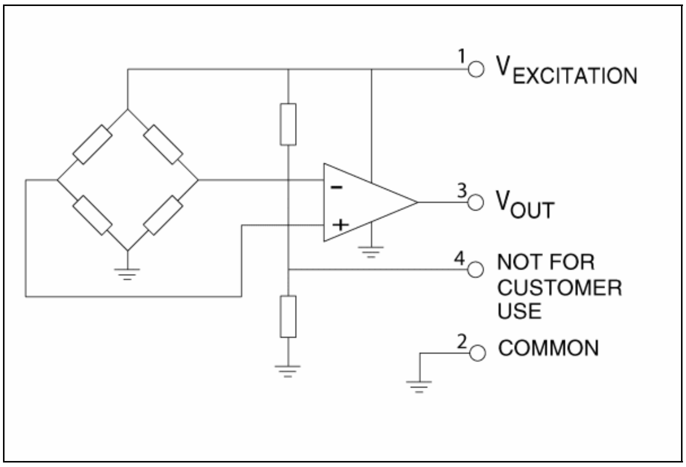
The crankshaft angle sensor also uses a *Transmissive Optoschmitt* Sensor to detect the current crankshaft angle with respect to the zero TDC position. In order to detect the crankshaft angle, 72- hole equally spaces have been made on the same aluminium disc used for the zero TDC sensor. It means that the space angle between two holes is 5 degrees.

The way of the crankshaft angle sensor work is similar to that of the zero TDC sensor. Instead of detecting only one hole, the crankshaft angle sensor detects the certain angle position of the crankshaft by counting the holes that have been detected. If the sensor detects a hole, the output will generate a high pulse (+5 volt). Therefore, the angle position of the crankshaft can be detected by counting the output pulses. In this case, one pulse represents angle of 5 degrees. The crankshaft angle sensor starts to count, when the zero TDC sensor encounters the zero TDC position. The output of this sensor is used by the ECU to count the current crankshaft angle position. Based on this information, the ECU can determine when to activate the injector.

6.12.5 MAP Sensor

The manifold absolute pressure (MAP) sensor utilizes a pressure sensor having pressure range of 0-1 in H_2O. The typical sensitivity of this sensor is 4 Volt per in H_2O. This sensor monitors the pressure of the air in the intake manifold. The amount of air being drawn into the engine can be used to represent the amount of power produced by the engine. The more air that enters the engine intake manifold, the lower the manifold pressure becomes. As such, this reading is used to measure how much power is being produced. The ECU reads the MAP sensors via Analog to Digital (ADC) port. The picture of this sensor is given in Figure 6.24.

(a)

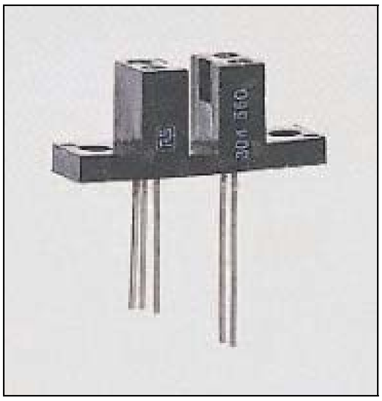


(b)

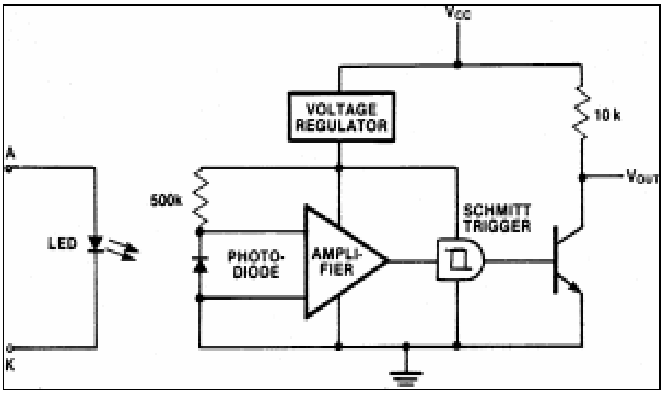
Figure 6.24: (a) MAP sensor (b) Schematic diagram

6.12.6 TDC Sensor

To locate the TDC position, the aluminium disc having a small hole is developed and attached to the engine output shaft. The position of this small hole when detected by the TDC sensor has to be match with the position of the zero TDC. Therefore this small hole functions as a mark to indicate the zero TDC position. The TDC sensor uses a sensor called as *Transmissive Optoschmitt* Sensor. The picture of this sensor can be seen in Figure 6.25.



(a)



(b)

Figure 6.25: (a) *Transmissive Optoschmitt* Sensor (b) Schematic diagram

The *Transmissive Optoschmitt* Sensor consists of an infrared emitting diode facing an *Optoschmitt* detector encased in a black thermoplastic housing. The output of the detector provides a high output (+5 volt) when the optical path is clear, meaning that the hole on the aluminium disc has been detected. The output of the detector gives a low output (0 volt) when the path is interrupted, meaning that the aluminium disc has blocked the path. The output of this TDC sensor is used to inform the Electronic Control Unit (ECU) that the Zero TDC has been detected.

6.12.7 Pressure Relief Valve

Pressure relief valve used is a *Swagelok* high-pressure proportional relief valve. Such valves open when the system reaches the set pressure and close when the system pressure falls below the set pressure. The valve is fitted with a spring kit which has a working pressure range between 24.1 and 51.7bar. During commissioning the spring will be adjust to provide the desired set pressure.

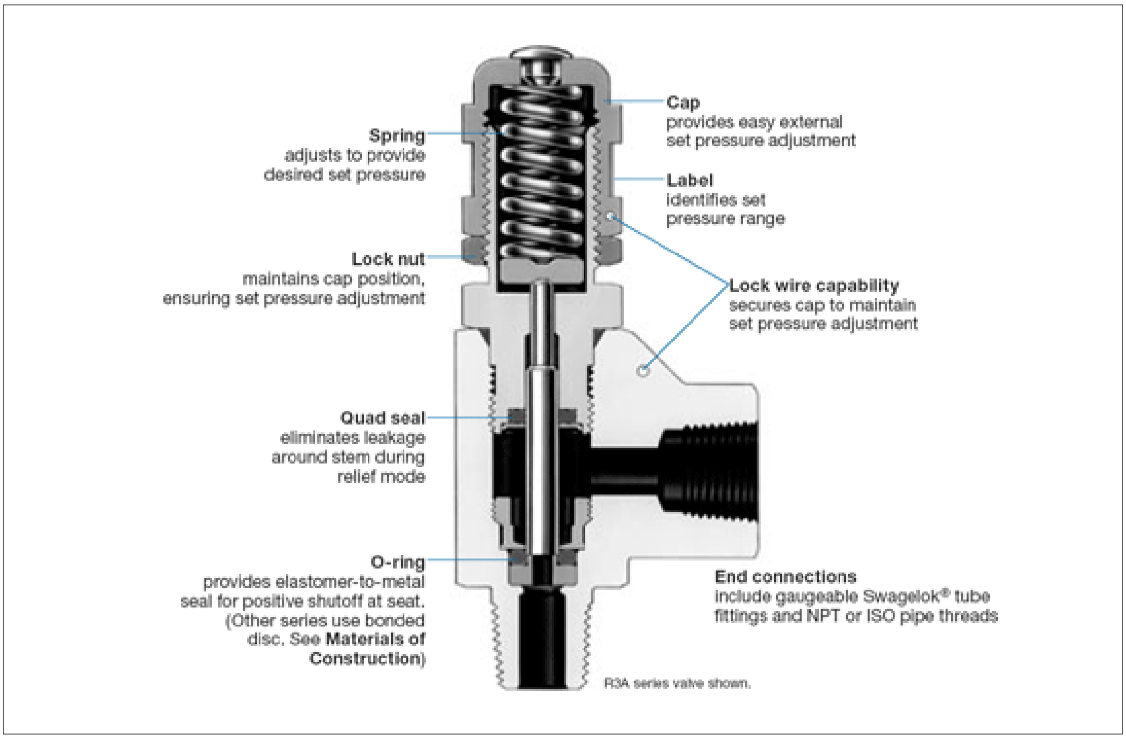


Figure 6.26: Sectional view of the PRV used in the GDI system of the prototype engine [13]

Chapter 7

SUMMARY

7.1 Conclusions

The following conclusions are hereby derived:

i) A small-size gasoline engine of stepped-piston design having a capacity of 125 cc has been successfully developed both for carbureted - and fuel-injection versions together with its auxiliary systems. Most of these works were implemented in-house using the facilities available in UTM.

ii) The improvements made on the carbureted version have strong indications of fuel having fuel economy, environmental-friendly features and comparable output to its conventional counterpart.

iii) The incorporation of four new features i.e. i) direct-fuel injector, ii) engine control unit (ECU), iii) dedicated lubricant dispenser and iv) engine crankcase breather have improved the engine performance and its associated HC and CO emissions.

iv) The engine design has been shown to demonstrate well at laboratory and field trial which in this case a mobile platform.

v) The program in realizing a small engine work was fully undertaken by local technologists and has been achieved.

Figure 7.1: The participation in SMIDEC 2005 in September 2005

7.2 Recommendations for Further Work

Even though this engine development program has accomplished its main goals there are still a number of work which when implemented will render the final product a more enhance small and mobile powerhouse for numerous uses. The works concerned are as follows:

i) *Optimization of the scavenging process*. At this stage the experimental work carried out still indicates a small fraction of the unburnt hydrocarbons being release from the engine tail-pipe. This is attributed to the small percentage of the charge being short-circuited prior to undergoing combustion especially at high speed. For optimization purposes the possible solution would be i) strategizing the transfer port and ii) the incorporation of the exhaust valve mechanism onto the engine.

ii) *Improve power-to-weight ratio*. Currently with the extras incorporated onto the engine the gross weight has escalate to 15 kg, with the engine producing 7.5 kW at 7500 rpm. For mobile automotive platform the power-to-weight ratio needs to further improvements (from currently 0.5 kW/kg) close to 1.0 kW/kg. To achieve this, the weight reduction must be visited and examined.

iii) *GDI reliability*. The exposure of the dedicated GDI unit to extreme and cyclic combustion processes has a detrimental effect on the overall performance of the fuel spray. To overcome this setback the materials of the GDI unit must be substituted with those able to withstand such punishing environment. A cooling technique must also be looked into and a possibility of other fuel metering technique such as indirect-injection through the transfer port using low pressure system must also be looked into.

iv) *Multi-cylinder configuration*. To explore the full potential of this engine concept, a multi-cylinder platform must be developed based on this design. By doing this, the incorporation of the GDI system and the valve mechanism will be fully rationalized and practical from the stand point of the auxiliary energy usage from the output of the engine.

LAMPIRAN 5

End of Project Report Guidelines

A. Purpose

The purpose of the End of Project is to allow the IRPA Panels and their supporting group of experts to assess the results of research projects and the technology transfer actions to be taken.

B. Information Required

The following Information is required in the End of Project Report:

- Project summary for the Annual MPKSN Report;
- Extent of achievement of the original project objectives;
- Technology transfer and commercialisation approach;
- Benefits of the project, particularly project outputs and organisational outcomes; and
- Assessment of the project team, research approach, project schedule and project costs.

C. Responsibility

The End of Project Report should be completed by the Project Leader of the IRPA-funded project.

D. Timing

The End of Project Report should be submitted within three months of the completion of the research project.

E. Submission Procedure

One copy of the End of Project is to be mailed to :

IRPA Secretariat
Ministry of Science, Technology and the Environment
14th Floor, Wisma Sime Darby
Jalan Raja Laut
55662 Kuala Lumpur

LAMPIRAN 5

End of Project Report

A. Project number : 03-02-06-0053 PR0005/03

Project title : DESIGN AND DEVELOPMENT OF AUXILIARY COMPONENTS FOR A NEW TWO-STROKE, STRATIFIED-CHARGE, LEAN-BURN GASOLINE ENGINE

B. Project leader: Prof Ir Dr Alias bin Mohd Noor

Tel: 07-5530500 **Fax: 07-5579385**

B. Summary for the MPKSN Report (for publication in the Annual MPKSN Report, please summarise the project objectives, significant results achieved, research approach and team structure)

Project Objective:

Design and development of a series of auxiliary components for an internal combustion engine. The component developments are for the improvement of the performance of a new design of two-stroke, single-cylinder, gasoline engine. The engine is based on a stepped-piston engine principle incorporating features for performance excellence i.e. high power-to-weight ratio, fuel economy, durable, low emission and multiple platform applications.

Significant Result achieved

The research group is able to produce the components for the single-cylinder two-stroke engine (demonstrator) whereby the engine is able to demonstrate environmental-friendly features (reduction in high hydro-carbon emissions) through the incorporation of these components developed by the group within the three-year period of the project. The features are : i) three-way induction port ii) direct fuel injection unit iii) engine control unit (ECU), iv) lubricant dispensing pump system for piston skirt lubrication. Currently the research group is still pursuing to optimize the power-to-weight ratio feature to make the prototype appealing to mobile platform use.

Research Approach

- **DESIGN EXERCISE**
  Concept analysis, Thermodynamics and mathematical simulation, working drawings (CAE), components development, manufacturing drawing (CAE) etc.

- **PROTOTYPING**
  Material procurement, consumables, fabrication and assembly, component integrity analysis, electronics and control system, fuelling system, air-intake system, calibration and measurement and exhaust gas after treatment device.

- **LABORATORY TRIALS**
  Rig development (for combustion and optical access investigation), flow visualisation, engine mapping (engine management system development) lubrication system investigation, ignition system optimisation overall performance test endurance test emission test, overall system optimisation and synchronisation test, tuning of the exhaust and intake, consultations.

- **FIELD TRIALS**
  Cyclic field trial investigation for durability and endurance (as prescribed by *SAE* procedures), fuel consumption and emission monitoring, instrumentation and data recordings, consumables, consultation and expert advice.

- **REFINEMENTS**
  `Fine tuning' of the engine components onto the newly developed engines for synchronisation giving optimised i) power-to-weight ratio and ii) packaging.

Project 3

- **COMPUTER SIMULATION**
  Theoretical work, acoustic theory for silencer attenuation characteristics, thermodynamics and mathematical simulation, NVH improvements, working drawings (CAE), components drawings, manufacturing drawing etc.

- **MATERIALS IDENTIFICATION AND FABRICATION TECHNIQUES**
  Materials (metal and non-metal) identification, properties, techniques of preparation and fabrication, assembly, component integrity analysis, structural study and mechanical testing

- **LABORATORY EXPERIMENTATION**
  Rig development (for noise and vibration investigation), performance evaluation of catalyst, flow visualisation, overall performance test, endurance test, emission test, overall system optimisation and synchronisation test, engine mapping etc.

- **TUNING FOR NOISE AND VIBRATION REDUCTION**
  improvement in the silencer design (examine for diffuser-type, side-resonant type and absorption type), positioning of silencer, laminar-flow optimisation, acoustical design for low-pass intake silencer and re-examine the intake system

- **FURTHER LABORATORY EXPERIMENTATION**
  Cyclic field trial investigation for noise radiation (as prescribed by *SAE* procedures) in conjunction of engine performance and emission, compliance test etc.

- **REFINEMENTS**
  `Fine tuning' of the intake, exhaust internal engine components and material utilisation for optimised performance: i) power-to-weight ratio, ii) fuel economy, iii) low emission, iv) noise reduction and v) attractive packaging.

Team Structure

The team structure is as follows:

Project : Design and Development of Auxiliary Components for the `Green' Two-Stroke Engines

Prof. Ir. Dr. Alias bin Mohd Noor – Head of Project
Prof. Ir. Dr. Azhar bin Abdul Aziz
Dr. Rosli bin Abu Bakar – researcher
Dr. Mardani Ali Sera – researcher
Mohd Fadzil bin Abdul Rahim – research officer
Gan Leong Meng - research officer (post-graduate student)
Devarajan A/L Ramasami – research Officer (post-graduate student)
Chong Chin Lee – research officer
Chin Kok Leong – research officer

C. Objectives achievement

- **Original project objectives** (Please state the specific project objectives as described in Section ll of the Application Form)

To design and develop auxiliary components to retrofit the newly developed two-stroke, stratified-charge, lean-burn engines (80cc and 125cc) to satisfy the requirements for high-power-to-weight ratio, fuel economy, durable, low emission and multiple platform applications.

- **Objectives Achieved** (Please state the extent to which the project objectives were achieved)

At the end of the program in August 2005 90% of the objectives set in this project have been achieved. The main achievement is the development auxiliary components for a workable engine prototype which was developed in parallel with this project by another research group within this R&D program. The high power-to-weight ratio, good performance and low emission features are being pursued outside the scope of the research program

- **Objectives not achieved** (Please identify the objectives that were not achieved and give reasons)

At the end of July 2005 the engine and all the auxiliaries are already in placed. When the auxiliary items are incorporated onto the prototype the power-to-weight ratio feature has exceeded 16 kg for an engine with maximum output of 9 kW. A 1:1 ratio would be ideal and is being pursued outside the scope of this R&D program.

D. Technology Transfer/Commercialisation Approach (Please describe the approach planned to transfer/commercialise the results of the project)

The transfer of the two-stroke engine technology (inclusive of the auxiliary component technology development) will be through i) licensing ii) joint-venture iii) education and iv) training to the Malaysian public and industries respectively. All these mechanism are considered as sustainable.

E. Benefits of the Project (Please identify the actual benefits arising from the project as defined in Section lll of the Application Form. For examples of outputs, organisational outcomes and sectoral/national impacts, please refer to Section lll of the Guidelines for the Application of R&D Funding under IRPA)

- **Outputs of the project and potential beneficiaries** (Please describe as specifically as possible the outputs achieved and provide an assessment of their significance to users)

  - Small engines, prime movers and motorcycles producers
  - Auxiliary components e.g. fuel injection unit, ECU and breather
  - Auto vendors and engine part makers
  - Malaysian public and industries

- **Organisational Outcomes** (Please describe as specifically as possible the organisational benefits arising from the project and provide an assessment of their significance)

  - Manpower development (1 PhD, 2 MSc)
  - New equipments
  - Improved facility
  - Recognition as a centre of Excellence (Automotive Development Centre, ADC)

- **National Impacts** (If known at this point in time, please describes specifically as possible the potential sectoral/national benefits arising from the project and provide an assessment of their significance)

  - Domestic industry linkages
  - Small and medium-scale industries (SMIs)
  - Improvement in the environment
  - Improvement in fuel utilisation
  - Wider choice and range of prime movers

F. Assessment of project structure

- **Project Team** (Please provide an assessment of how the project team performed and highlight any significant departures from plan in either structure or actual man-days utilised)

Name[1]	Organisation	Man-months[1] on project
Project Leader (Please provide name) Prof Ir Dr Alias bin Mohd Noor	UTM	6
Programme Head (Please provide name)	UTM	-
Researchers (Please provide names or numbers of researchers) Prof. Ir. Dr. Azhar bin Abdul Aziz Dr. Rosli bin Abu Bakar Chong Chin Lee –Research officer Chin Kok Leong – research officer	ADC, UTM ADC, UTM ADC, UTM ADC, UTM	84
Support Staff (Please indicate how many) 4	ADC, FKM, UTM	24
Contract Staff (Please indicate how many) 4 (Local research students)		96
	Total	210

- **Collaborations** (Please describe the nature of collaborations with other research organisations and/or industry)
  - MOFAZ Sdn. Bhd.
    - provider of platform in which the prototypes can be tested in actual working environment
  - HL Yamaha Motor Research Centre Sdn. Bhd.
    - provider of technical expertise for laboratory and field trials activities
  - MZ-Motorrad Sdn. Bhd – Motor cycle assembler
  - Edaran Modenas Sdn. Bhd.
    - Provider of component testing facilities

G. Assessment of Research Approach (Please highlight the main steps actually performed and indicate any major departure from the planned approach or any major difficulty encountered)

- Flow, combustion, ignition, lubrication and heat transfer studies/analyses

- Fuel System Development
  - Carburettor for the 80 cc version
  - Fuel semi-direct injection system and carburettor for 125 cc version
  - Possibility of air-assisted fuel injector in two-stroke engine applications
  - Skip-injection control to avoid misfiring at idling stage
  - Fully digital electronic fuel injection system

- Ignition system
  - Optimisation of current ignition system
  - Design of ignition circuit

- Engine Management System
  - Optimisation of fuel utilisation through feedback control system, identification of sensing parameters

- Intake and System Development
  - Investigation into the use of the Intake valve(s)
  - Development of oxidation catalyst and engine muffler/silencer
  - Experimental study of gas flow through reed valve
  - Use of exhaust pipe expansion chamber

- Lubrication System Development
  - Development of separate lubrication system

- Cooling System Development
  - air-cooled for the 50 cc utility engines
  - water-cooled system for the 125 cc engines

- Components Integration
  - Integration of the components to the newly produced engines (prototypes)

- Manufacturing Processes
  - Identification of the processes involved from design to development of components
  - Costing

- Performance Evaluation: Laboratory & Field Trial.
  - Exhaustive evaluation for overall performance
  - Rig development for individual component evaluation

- Components refinement

- Re-evaluation
  - Laboratory and field trials

I. **Assessment of Project Costs** (Please comment on the appropriateness of the original budget and highlight any major departure from the planned budget)

The overall expenditure of the project was RM x,xxx,xxx.xx from the allocation given by MOSTE in 2002 which was RM 7,236,264.00. The reduction in expenditure was due to the efforts made by the group not to engage foreign consultant(s) in the development of some critical parts (namely ECU and injector), as during the implementation of the project local fabricators were able to be identified. Added to this was the ability to utilize local experts within UTM to undertake design and analyses work, which have added to the cost-saving efforts.

J. **Additional Project Funding Obtained** (In case of involvement of other funding sources, please indicate the source and total funding provided)

None

K. **Other Remarks** (Please include any other comment which you feel is relevant for the evaluation of this project)

The time frame was rather limited due to prolonged period of equipment procurement exercises and "heavy" university procedures in which the group needs to comply. The sudden withdraw of some supporting staff (RO/RA) due to job offers in someway hampers the smooth running of the program. The financial allocation is very sufficient and the research group appreciates the help of MOSTI throughout the implementation of this program.

UNIVERSITI TEKNOLOGI MALAYSIA
Research Management Centre

PRELIMINARY IP SCREENING & TECHNOLOGY ASSESSMENT FORM
(To be completed by Project Leader submission of Final Report to RMC or whenever IP protection arrangement is required)

1. **PROJECT TITLE IDENTIFICATION** :

Design And Development Of Auxiliary Components For A New Two Stroke, Stratified-Charge, Lean-Burn Gasoline Engine Vote No: 74516

2. **PROJECT LEADER** :

Name : Prof Ir Dr Hj Alias bin Mohd Noor .

Address : Fakulti Kejuruteraan Mekanikal, .

Universiti Teknologi Malaysia, .

81310 UTM Skudai. Johor Bahru. .

Tel : 07-5530500 Fax : 07-5579385 e-mail : alias@fkm.utm.my

3. **DIRECT OUTPUT OF PROJECT** *(Please tick where applicable)*

Scientific Research	Applied Research	Product/Process Development
☐ Algorithm	☐ Method/ Technique	☐ Product/ Component
☐ Structure	☐ Demonstration / Prototype	☐ Process
☐ Data	☐	☐ Software
☐ Other, please specify ----------------------------	☐ Other, please specify ----------------------------	☐ Other, please specify -----------------------------

4. **INTELLECTUAL PROPERTY** *(Please tick where applicable)*

☐ Not patentable
☐ Patent search required
☐ Patent search completed and clean
☐ Invention remains confidential
☐ No publications pending
☐ No prior claims to the technology
☐ Technology protected by patents
☐ Patent pending
☐ Monograph available
☐ Inventor technology champion
☐ Inventor team player
☐ Industrial partner identified

5. LIST OF EQUIPMENT BOUGHT USING THIS VOT

Computer software, Pressure sensors, EMS Kit, Combustion analyzer, Engine dynamometer, Swirl and laminar flow test rig, Crank angle encoder, Combustion pressure sensor, Spectrum analyzer.

6. STATEMENT OF ACCOUNT

a)	APPROVED FUNDING	RM : …2,006,000.00………
b)	TOTAL SPENDING	RM : …1,773,304.15………
c)	BALANCE	RM : …232,695.85…………

7. TECHNICAL DESCRIPTION AND PERSPECTIVE

Please tick an executive summary of the new technology product, process, etc., describing how it works. Include brief analysis that compares it with competitive technology and signals the one that it may replace. Identify potential technology user group and the strategic means for exploitation.

a) Technology Description

b) Market Potential

c) Commercialization Strategies

8. RESEARCH PERFORMANCE EVALUATION

a) FACULTY RESEARCH COORDINATOR

	Excellent	Very Good	Good	Satisfactory	Fair	Weak
Research Status	( )	( )	( )	( )	( )	( )
Spending	( )	( )	( )	( )	( )	( )
Overall Status	( )	( )	( )	( )	( )	( )

Comment/Recommendations :

…………………………………………

Signature and stamp of
JKPP Chairman

Name : ……………………………………

Date : ……………………………………

b) RMC EVALUATION

Research Status	( )	( )	( )	( )	( )	( )
Spending	( )	( )	( )	( )	( )	( )
Overall Status	( )	( )	( )	( )	( )	( )
	Excellent	Very Good	Good	Satisfactory	Fair	Weak

Comments:-

Recommendations :

☐ Needs further research

☐ Patent application recommended

☐ Market without patent

☐ No tangible product. Report to be filed as reference

……………………………………………………….

Name : ……………………………………………

Signature and Stamp of Dean / Deputy Dean

Research Management Centre

Date : ……………………………………………

Lampiran 20

UTM/RMC/F/0024 (1998)

UNIVERSITI TEKNOLOGI MALAYSIA

BORANG PENGESAHAN
LAPORAN AKHIR PENYELIDIKAN

TAJUK PROJEK : **Design and Development of Auxiliary Components for a New Two-Stroke, Stratified-Charge, Lean-burn Gasoline Engine**

Saya **Prof Ir Dr Alias bin Mohd Noor**
(HURUF BESAR)

Mengaku membenarkan **Laporan Akhir Penyelidikan** ini disimpan di Perpustakaan Universiti Teknologi Malaysia dengan syarat-syarat kegunaan seperti berikut :

1. Laporan Akhir Penyelidikan ini adalah hakmilik Universiti Teknologi Malaysia.
2. Perpustakaan Universiti Teknologi Malaysia dibenarkan membuat salinan untuk tujuan rujukan sahaja.
3. Perpustakaan dibenarkan membuat penjualan salinan Laporan Akhir Penyelidikan ini bagi kategori TIDAK TERHAD.
4. * Sila tandakan (/)

☐ SULIT (Mengandungi maklumat yang berdarjah keselamatan atau Kepentingan Malaysia seperti yang termaktub di dalam AKTA RAHSIA RASMI 1972).

☐ TERHAD (Mengandungi maklumat TERHAD yang telah ditentukan oleh Organisasi/badan di mana penyelidikan dijalankan).

☐ TIDAK TERHAD

____
TANDATANGAN KETUA PENYELIDIK

____
Nama & Cop Ketua Penyelidik

Tarikh : _________________

CATATAN : ** Jika Laporan Akhir Penyelidikan ini SULIT atau TERHAD, sila lampirkan surat daripada pihak berkuasa/organisasi berkenaan dengan menyatakan sekali sebab dan tempoh laporan ini perlu dikelaskan sebagai SULIT dan TERHAD.*

Benefits Report Guidelines

A. Purpose

The purpose of the Benefits Report is to allow the IRPA Panels and their supporting experts to assess the benefits derived from IRPA-funded research projects.

B. Information Required

The Project Leader is required to provide information on the results of the research project, specifically in the following areas:

- Direct outputs of the project;
- Organisational outcomes of the project; and
- Sectoral/national impacts of the project.

C. Responsibility

The Benefits Report should be completed by the Project Leader of the IRPA-funded project.

D. Timing

The Benefits Report is to be completed within three months of notification by the IRPA Secretariat. Only IRPA-funded projects identified by MPKSN are subject to this review. Generally, the Secretariat will notify Project Leaders of selected projects within 18 months of project completion.

E. Submission Procedure

One copy of this report is to be mailed to :

IRPA Secretariat
Ministry of Science, Technology and the Environment
14^{th}, Floor, Wisma Sime Darby
Jalan Raja Laut
55662 Kuala Lumpur

Benefit Report

1. Description of the Project

A. Project identification

1. Project number : 03-02-06-0054 PR0005/03

Project title : Design and Development of Auxiliary Components for a New Two-Stroke, Stratified-Charge, Lean-burn Gasoline Engine

2. Project leader : Prof Ir Dr Alias bin Mohd Noor

B. Type of research

Indicate the type of research of the project (Please see definitions in the Guidelines for completing the Application Form)

- [ ] Scientific research (fundamental research)
- [x] Technology development (applied research)
- [ ] Product/process development (design and engineering)
- [ ] Social/policy research

C. Objectives of the project

1. Socio-economic objectives

Which socio-economic objectives are adressed by the project? (Please indentify the sector, SEO Category and SEO Group under which the project falls. Refer to the Malaysian R&D Classification System brochure for the SEO Group code)

Sector :	Manufacturing
SEO Category :	Manufacturing
SEO Group and Code :	Transport Equipment (S20611)

2. Fields of research

Which are the two main FOR Categories, FOR Groups, and FOR Areas of your project? (Please refer to the Malaysia R&D Classification System brochure for the FOR Group Code)

a. Primary field of research

FOR Category :	Mechanical and Industrial Engineering
FOR Group and Code :	F 10701
FOR Area :	Automotive Engineering

b. Secondary field of research

FOR Category :	Mechanization and Design Engineering
FOR Group and Code :	F 10710
FOR Area :	Automotive Engineering

D. **Project duration**

What was the duration of the project?

39 Months (actual)

E. **Project manpower**

How many man-months did the project involve?

546 Man-months

F. **Project costs**

What were the total project expenses of the project?

RM 1,773,304.15

G. **Project funding**

Which were the funding sources for the project?

Funding sources	Total Allocation (RM)
IRPA	RM2,006,000.00

ll. Direct Outputs of the Project

A. Technical contribution of the project

1. What was the achieved direct output of the project :

For scientific (fundamental) research projects?

- [ ] Algorithm
- [ ] Structure
- [ ] Data
- [ ] Other, please specify : -

For technology development (applied research) projects:

- [ ] Method/technique
- [ ] Demonstrator/prototype
- [ ] Other, please specify : Methodology of small engine development

For product/process development (design and engineering) projects:

- [ ] Product/component
- [ ] Process
- [ ] Software
- [ ] Other, please specify : ____

2. How would you characterise the quality of this output?

- [ ] Significant breakthrough
- [ ] Major improvement
- [ ] Minor improvement

B. Contribution of the project to knowledge

1. How has the output of the project been documented?

- [ ] Detailed project report
- [ ] Product/process specification documents
- [ ] Other, please specify : ____

2. Did the project create an intellectual property stock?

- [ ] Patent obtained
- [ ] Patent pending
- [ ] Patent application will be filed
- [ ] Copyright

3. What publications are available?

- [ ] Articles (s) in scientific publications — How Many: 2
- [ ] Papers(s) delivered at conferences/seminars — How Many: 12
- [ ] Book
- [ ] Other, please specify : 3 newspaper articles (NST, Star and Utusan Malaysia)

4. How significant are citations of the results?

- [ ] Citations in national publications — How Many: ________________
- [ ] Citations in international publications — How Many: ________________
- [ ] None yet
- [ ] Not known

lll. Organisational Outcomes of the Project

A. Contribution of the project to expertise development

1. How did the project contribute to expertise?

- [ ] PhD degrees — How Many: 1
- [ ] MSc degrees — How Many: 6
- [ ] Research staff with new specialty — How Many: 2
- [ ] Other, please specify: Enhancement of academic staffs in small engine work

2. How significant is this expertise?

- [ ] One of the key areas of priority for Malaysia
- [ ] An important area, but not a priority one

B. Economic contribution of the project?

1. How has the economic contribution of the project materialised?

- [ ] Sales of manufactured product/equipment
- [ ] Royalties from licensing
- [ ] Cost savings
- [ ] Time savings
- [ ] Other, please specify : ____

2. How important is this economic contribution?

[ ] High economic contribution	Value:	RM________________
[ ] Medium economic contribution	Value:	RM________________
[ ] Low economic contribution	Value:	RM 40-50,000,000.00

(if the technology developed is adopted)

3. When has this economic contribution materialised?

- [ ] Already materialised
- [ ] Within months of project completion
- [ ] Within three years of project completion
- [ ] Expected in three years or more
- [ ] Unknown

C Infrastructural contribution of the project

1. What infrastructural contribution has the project had?

- [ ] New equipment Value: RM 4,217,401
- [ ] New/improved facility Investment: RM 80,000.00
- [ ] New information networks
- [ ] Other, please specify: information centre for small engine development

2. How significant is this infrastructural contribution for the organisation?

- [ ] Not significant/does not leverage other projects
- [ ] Moderately significant
- [ ] Very significant/significantly leverages other projects

D. Contribution of the project to the organisation's reputation

1. How has the project contributed to increasing the reputation of the organisation

- [ ] Recognition as a Centre of Excellence
- [ ] National award
- [ ] International award
- [ ] Demand for advisory services
- [ ] Invitations to give speeches on conferences
- [ ] Visits from other organisations
- [ ] Other, please specify: spin-off for the developments of small mobile platforms such as unmanned aerial vehicles and unmanned water craft

2. How important is the project's contribution to the organisation's reputation ?

☐ Not significant

☐ Moderately significant

☐ Very significant

1V. National Impacts of the Project

A. Contribution of the project to organisational linkages

1. Which kinds of linkages did the project create?

- [ ] Domestic industry linkages
- [ ] International industry linkages
- [ ] Linkages with domestic research institutions, universities
- [ ] Linkages with international research institutions, universities

2. What is the nature of the linkages?

- [ ] Staff exchanges
- [ ] Inter-organisational project team
- [ ] Research contract with a commercial client
- [ ] Informal consultation
- [ ] Other, please specify: Testing and development of small engine parts

B. Social-economic contribution of the project

1. Who are the direct customer/beneficiaries of the project output?

Customers/beneficiaries:	Number:
Manufacturer of two-wheeler motorcycles	Two (MZ-Motorrad & Mofaz Sdn. Bhd.)

2. How will the socio-economic contribution of the project materialised?

- [ ] Improvements in health
- [ ] Improvements in safety
- [ ] Improvements in the environment
- [ ] Improvements in energy consumption/supply
- [ ] Improvements in international relations

Other, please specify: ____

3. How important is this socio-economic contribution?

- [ ] High social contribution
- [ ] Medium social contribution
- [ ] Low social contribution

4. When has/will this social contribution materialised?

- [ ] Already materialised
- [ ] Within three years of project completion
- [ ] Expected in three years or more
- [ ] Unknown

Date: 22/2/2006 **Signature:**