Design and Fabrication of Erect Rotary Valve for Internal Combustion Engine

by

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ABSTRACT

The internal combustion engine, performing mechanical work by harnessing combustion, has proved to be a convenient, efficient and reliable path in the last decades. However, the complexity of the inner structures and mechanisms act as the essential barrier which limits the further improvement of the internal combustion engine. The valve train, the structure that operates the combination gas exchange, contributes its friction to the internal mechanism loss which consumes power and confines the thermal efficiency. Based on the shape and operation of conventional poppet valves, a manufacturer has to sacrifice the piston top design and compression ratio to prevent valve-piston interference.

This innovational research focuses on not only the valve train structure and driving method but also the shape and operating condition of the valve itself. As a new valve design, a unique Erect Located Cone Rotary Valve will be spinning inside of the combustion chamber to operate combination gas exchange.

The thesis introduces the history of the internal combustion engine and the classification of the valve configuration. The research exposes the problems of the conventional poppet valve and discusses the advantages and limitations of previous rotary valve designs. The thesis presents detailed analysis, calculation and parameters of the erect rotary valve and also describes the limitation and the compromise of the current erect rotary valve design. In the end, the research provides the feasibility and direction of future development.

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CHAPTER ONE. LITERATURE REVIEW

Similar to the conventional poppet valve configuration, the transverse layout rotary valve is the most direct conversion for the original piston internal combustion engine.

Usually, varies between different engines and valve train configurations, the valve train contributes up to around 25 percent of the total internal friction. For example, in the study of Valvetrain Friction [1], the members of Automobili Lamborghini, Calabretta and Cacciatore introduced that based on motored strip measurements, valve train contributes 35 percent of total friction at 1000 revolutions per minute (RPM). The percentage of valve train reduces with engine speed. Based on the measurement, valve contributes around 10 percent of total friction when the engine is over 6000 RPM. They also indicated that the valve train friction of high performance engine is relatively higher.

During study of combustion in a high-speed rotary valve spark-ignition engine [2] that was been done by Chow, Watson and Wallis, the combustion model was designed to simulate the combustion performance for a transverse rotary valve engine at up to 18000 RPM of engine speed. The data gathered from this experiment helped indicate the paths to improvement for the engine combustion process. As the conclusion shows, engine power output increases with volumetric efficiency. In-cylinder velocity, regarding to RPM, contributes to the engine power output with its increase.

Bishop Innovations developed its dual ports single rotary valve. According to the research [3] that was published in 2007, instead of a timing chain/belt, the Bishop rotary valve engine uses a string of timing gears to transfer the power from the crankshaft to the rotary valve. Incorporating both the intake and exhaust ports into a single column valve, the Bishop rotary valve is able to occupy the most space above the cylinder and exchange the gases with larger ports for both the intake and exhaust. The rotational motion of the rotary valve removes the inertia of the reciprocating poppet valve. The researchers developed a seal similar to piston rings that sits around the rotary valve vent and slightly preloaded to push against the contacting surface to form a proper seal. One approach shows that the weight reduction is significant by building a 3-liter V10 F1 rotary valve engine which is around 80kg and 16kg less than the engine that has the poppet valve. The research also indicated that performance remains as high as the performance of the poppet valve engine and the peak volumetric efficiency is the same as the poppet valve engine.

The research [4] that Boretti and Scalzo published, optimized the pneumatic poppet valve and also designed a rotary valve which provides ultra-sharp valve opening and closing. Described by this research, a rotary valve has its capacity to improve the volumetric efficiency by providing the largest valve area in a short time. In their rotary valve engine design, the compression ratio was set up to 14:1. The achievement of their rotary valve includes higher power density, better engine breathing properties, higher fuel conversion efficiency and reduction of weight.

Boretti's earlier research [5] that was finished with Jiang and Scalzo also indicated that rotary valve could provide a chance for the engine to gain a higher compression ratio. They also included Bishop Innovations' achievement that solved gas sealing, oil sealing, excessive friction and seizure caused by thermal and mechanical distortion and the dual ports single valve was successful on F1 racing cars from 1995 to 2005 in reaching 20000 to 24000 RPM. However, later rules of F1 were introduced by The Fédération Internationale de l'Automobile (FIA) limited the improvement the development of the rotary valve. According to Formula One Technical Regulations 2007, "Only reciprocating poppet valves are permitted." [6] Their modelling results proved the engine will have high speed, high pressure fuel injection which allows shorter injection times. The research also indicated that the gas flow will be different from the poppet valve engine due to the lack of piston top pockets which clears the piston from the valves.

The study that done by Muroki, Moriyoshi and Sekizuka in 1999 focused on the flow dynamic and the friction effect. The driving mechanical loss of the rotary valve is up to 40 percent less than the one that measured in the poppet valve mechanism. However, the notch profile in early stage of the intake stroke would affects the intake flow. This also proved in the discussion in [7].

Muzakkir, Patil and Hirani also conducted a study of innovative engine valve design [8] in early 2015 in which the study hypothesized an erect rotary valve would work with a Magneto-Rheological fluid instead of a solid metal valve seat to form a proper sealing and prevent wearing out. However, none has fabricated and tested this configuration of rotary valve.

For the extended application, the rotary valve is also practical on a pneumatic machine which is the opposite operation of the internal combustion engine. In the research of the high speed pneumatic application rotary valve [9], Brown, Atluri and Schmiedeler, which differs from Bishop Innovation, introduced a set of floating valve seals. The spring will push the floating valve seal against the rotary valve to seal the contact surface and self-adjusts to accommodate the wearing out.

The research [10] published in 2014 shows that Zibani, Chuma and marumo designed, tested and implemented a rotary valve control unit for a single cylinder engine. This research addresses the problems of piston-valve interference and the complexities of the conventional valve train on the poppet valve engine. The software operated electronically controlled rotary valve (ECRV) manages the system and offers fully flexible valve event control. According to the research, the throttle valve is also removable to reduce the pumping loss. Since the engine control unit successfully operated the experimental system, the idea of extending the electronically controlled rotary valve into a multi-cylinder engine in now feasible. The feature of the electric rotary valve also provides the possibility for variable timing control.

CHAPTER TWO. INTRODUCTION

Instead of powering a transmission through the crankshaft with a repeating combustion, the origins of the internal combustion engine was utilizing combustion to lift a giant weight, dating back to the Renaissance. [11] By igniting fuel inside of the vertical sit cylinder, the combustion would drive a piston upward and then the atmospheric pressure pulls the piston back due to cooling down of the explosive gases. [12]

However, the internal combustion engine which is utilizable for automobiles that we know today originated in 1876 when Otto first introduced the spark-ignition engine and in 1892 when Diesel created the compression-ignition engine. [13] Ever since, research in internal combustion engine operation has developed a variety of engine designs to experimentally increase the performance, efficiency and reliability.

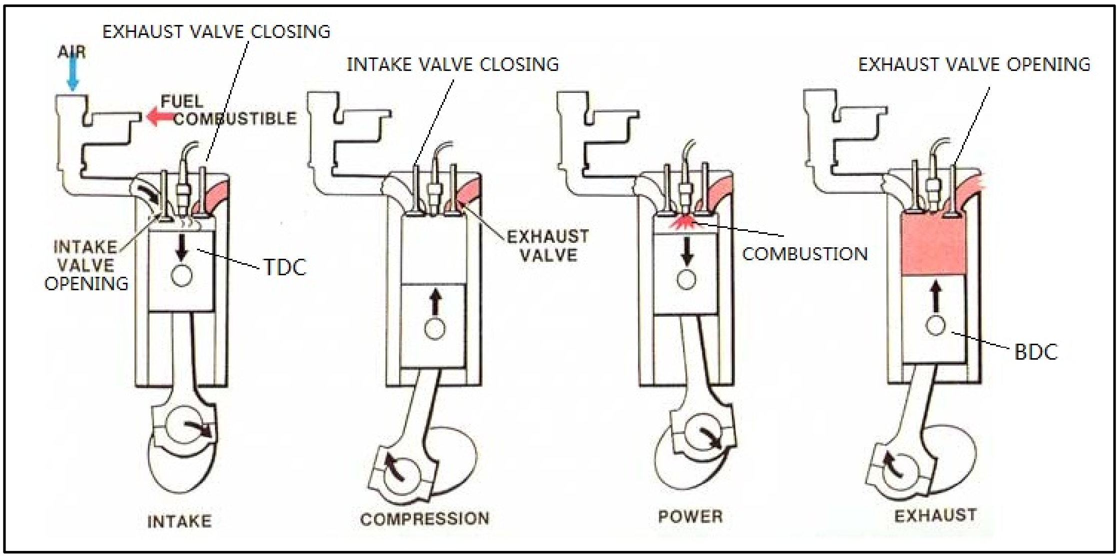

Figure 1: Four-Stroke Engine Principle

The four-stroke internal combustion engine, generally practiced as the power source for automobiles, requires four piston strokes which contributes to two crankshaft revolutions for each power cycle. As shown in figure 1, with opening the intake valve, the engine starts at Top Dead Center (TDC) where is the highest point that piston can go and aspirates air/fuel mixture into the cylinder. After the intake stroke, with closing the intake valve, piston passes Bottom Dead Center (BDC) and goes upward to compress the mixture. At the end of the compression stroke, either spark plug (gasoline engine) or compression heat (diesel engine) ignites the mixture when piston is at TDC. The expanded combustion gaseous product pushes piston downward for the expansion stroke. Finally, piston passes BDC and goes back up while exhaust valve opens to release the exhaust gases.

Despite multiple subsystems, such as, oil pump, alternator and cooling system, etc., the valve train could be the most influential component of four-stroke engine design. It is responsible for exchanging air/fuel mixture and exhaust gas between the cylinder and atmosphere. Numbers of different valve designs were experimented on the internal combustion engines in the past centuries and people had got into an agreement that the poppet valve is the most popular attributing to its durability and ease of arrangement inside of combustion chamber.

The internal combustion engine’s continuous development generated numbers of valve train configurations in the past decades. Some of them proved to be eminent to operate gases exchange for engine properly, such as, pushrod mechanism and overhead camshaft design. Besides these, due to a variety of adverse effects manufacturers discarded many defective structures, such as, the slide valve and sleeve valve.

Pushrod Valve System

The camshaft for a pushrod type engine is usually located at the center section of the engine block beside the cylinder which connects to rocker arm at the top through a pushrod and its lifter. The rocker arm acts as a lever which pushes valve to be open when the pushrod lifts up. Figure 2 shows the diagram of the pushrod valve train.

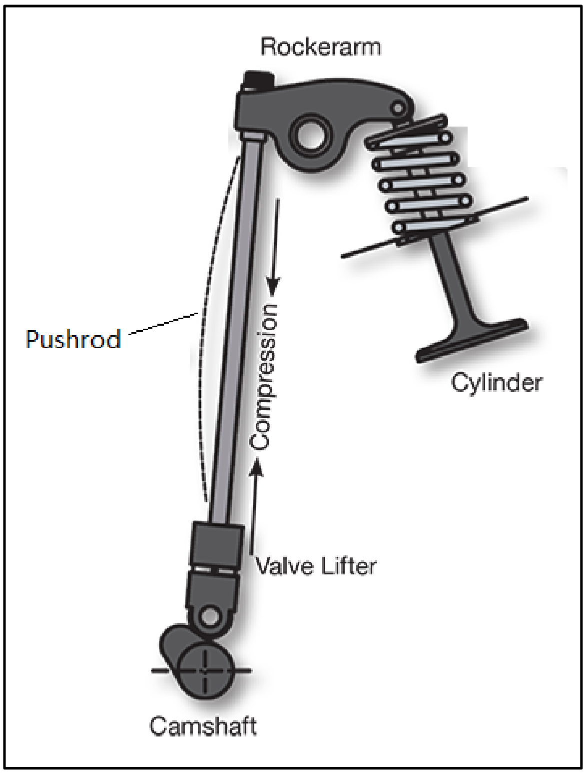

Figure 2: Pushrod Valve Mechanism

However, because of weight sensitivity in the valve train, the engine utilizing pushrod valve design will usually be limited on the aspect of engine revolution speed. Both pushrod and lifter contribute a considerable amount of weight in the valve train. According to the working method of four-stroke engine, calculation shows that at 4000 revolution per minute (RPM), a valve will open 2000 times every minute (33 times a second). A heavy valve train will keep its motion further until valve spring catches it due to its inertia causing valve floating and valve-piston interference to occur. [14]According to General Motors, the LS3, which is the most famous small block 6162-cc V-8 naturally aspirated high performance gasoline engine, which produces 415 horsepower at 5900 RPM on its 2014 version, however, the maximum engine speed is limited at only 6600 RPM because of the limitations discussed above. [15] Figure 3 exhibits the damage when valve-piston interference occurs.

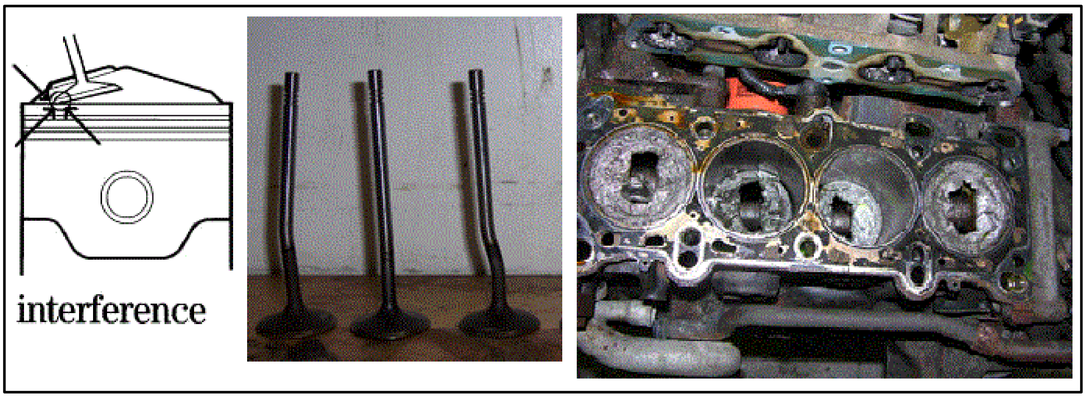

Figure 3: Valve-Piston Interference and Its Damage

Overhead Camshaft Valve System

Indeed, by removing the entire set of pushrod and even rocker arm, an overhead camshaft valve system discovers a new world at higher revolution speed range. According to figure 4, leading power from crankshaft through either timing chain or belt, camshaft drives valve directly from the top of cylinder head with lifter. Obviously, one of the popular competitors of GM LS3, Mercedes-Benz M159 6208-cc V-8 naturally aspirated gasoline engine, generates 622 horsepower at 7400 RPM on its 2013 version and the engine speed limit (redline) is marked at 8000 RPM. [16]

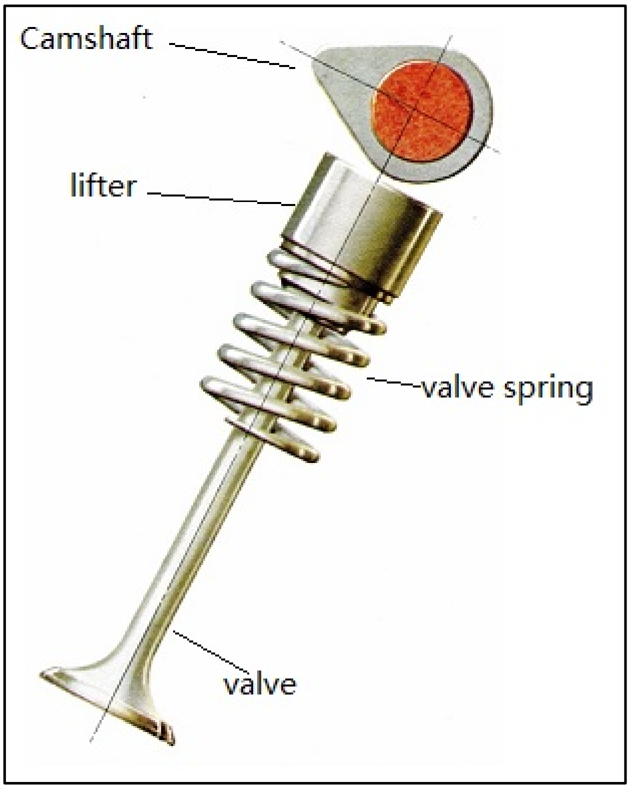

Figure 4: Overhead Camshaft Valve Mechanism

Although, they are not the same engine with only different valve train configurations, one can still indicate the tremendous difference on the improvement of maximum revolution speed. Nevertheless, for conventional poppet valve designed engine, in order to solve floating problem at much higher revolution speed range (over 10000 RPM), stronger valve springs are necessarily involved, which, in the contrary, increases wear and power needed to lift the valve.

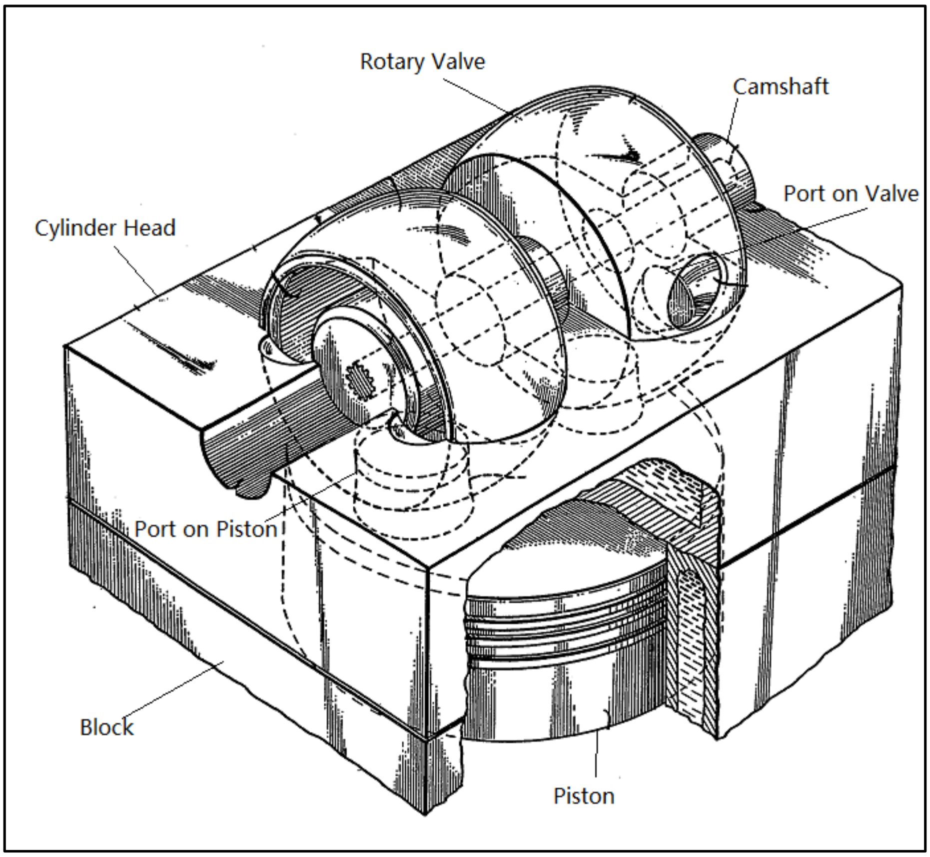

Figure 5: SOHC Transverse Rotary Valve

The circle, a perfect pattern in nature, performed its merit to realize a variety of objectives in the reality. Even the conventional valve was also been fabricated into a round shape. However, its linear reciprocating motion sets it back due to its inertia.

Every time the valve starts or stops moving, inertia resists its change in state of movement. In order to eliminate the effect of inertia, the rotary valves emerged. As shown in figure 5, instead of linear reciprocating motion, a rotary valve spins itself to exchange gases through its vents or tunnels but sealing and size, etc. are still to be determined. This research will be focusing on the study as well as the fabrication of a special type of rotary valve which eliminates valve floating, valve-piston interference, and inertia influence. The modifications will complement the existed transverse rotary valve's advantages and eliminate its disadvantages. Another goal of this research is providing the feasibility of individual control for each single valve separately.

CHAPTER THREE. OBJECTIVE

The research will go over the most major problems that exist in the present valve configurations. With the survey, the thesis will indicate the key elements and root causes of the problems. The research will also focus on the problems accordingly and present the corresponding solutions and new designs on the new engine valve configuration.

Utilizing an existing 1996 Suzuki 200cc four-stroke chain type single overhead camshaft single cylinder engine, the research requires light modification to the cylinder head. Contributing to its compatibility, most of existing engine components will be reusable after certain modifications. The original data of the engine needs to be measured and documented as the base data reference for future parts fabricating. Removal of original poppet valve train parts is necessary to clear space for the new valve.

In order to start and run the engine properly, calculation of essential data is the first goal, For example, the valve open area and valve train drive ratio. This research will set every parameter back to be the same as the original engine so the comparison of performance between the before and after will be feasible.

The second goal of the research is to design and develop the necessary parts and modifications of the existed ones. This includes indicating the operational defects in the originally designed valve systems, such as, interference problem, reliability, sealing problem and oil consumption problem, etc., modifying the camshaft to fit the cylinder head, and building rotary valve and its case to convert the engine into a rotary valve equipped one.

The final goal of this research is to build a more advanced knowledge structure of rotary valve engine, prove its feasibility and the opportunity of individual control. The research will also analyze the direction of future research identify the weaknesses of the rotary valve.

CHAPTER FOUR. THEORY

Performance

Indicated Horsepower

Under a completely frictionless situation, by calculating the expanding combustion energy in the cylinder, one can indicate the expected theoretical power produced by an internal combustion engine. Unlike shaft horsepower, indicated horsepower does not count the realistic power losses such as internal friction, waste heat and impropriate sealing, etc. In other words, by controlling variations during the modifications in this research, the changes can easily be determined by the modified parts by differences of indicated horsepower and shaft horsepower on both original and modified engine.

The following formula describes Indicated horsepower. [17]

$$\text{ip} = \frac{(imep)LAnK}{60 \times 1000}$$

Where,

ip= indicated power (kW)

imep= indicated mean effective pressure (kN/m^2)

L= length of stroke (m)

A= cross-sectional area of piston (m^2)

n= number of power strokes (n=N/2 for four-stroke engine)

N= crankshaft speed (RPM)

k=number of cylinders

Volumetric Efficiency

A primary aspect of how much power can be generated from combustion is the intake stroke when the piston's downward motion creates a vacuum and aspirates the air/fuel mixture into the cylinder. However, an unideal condition is caused by flow restrictions which allows less than an ideal amount of mixture to enter the cylinder. [18] This is called pumping loss which is described by the term volumetric efficiency as the following equation. [18]

$$\eta_v = \frac{n_r \dot{m}_a}{\rho_a V_d N}$$

Where:

η_v= volumetric efficiency

n_r= number of revolutions per cylinder

$\dot{m}_a$= steady-state flow of are into the cylinder

ρ_a= air density

V_d= displacement volume

N= engine speed

Usually, air density can be defined by standard values of surrounding air pressure and temperature which are

$$P_0 = 101\ kPa = 14.7\ psia$$

$$T_0 = 295\ K = 25°C = 77°F$$

respectively.

Valve

Based on the principle of conventional poppet valve design (figure 2, figure 4), the main task of the valve is to open and close according to engine operating timing to ensure that cylinder breaths properly. Valve timing, lift and duration are the key elements of the gas exchange performance, which determined is by camshaft specification and operation timing. The requirement of gas exchange varies under different performance request, such as revolution speed range and fuel. Automobile or engine manufacturers developed Variable Valve Timing system which changes valve timing and/or lift to optimize engine performance and accommodate various working conditions.

Valve Opening Area

The intake valve itself offers the greatest restriction to the air flow, which decreases volumetric efficiency dramatically. [19] Valve opening area is the factor that is determined by valve lift and size. Manufacturers also applied multi-valve technology on modern engine to increase valve opening area by adding more valves per cylinder. Enlarging valve opening area allows more air to run into the cylinder, which increases volumetric efficiency. Larger valve opening area also means less restriction to air flow, which reduces pumping loss and raises overall engine efficiency. [19] The following equation describes valve opening area.

$$\mathrm{A} = \pi d_v l$$

Where,

A= valve opening area

d_v= valve diameter

l= valve lift

For extreme large valve lift, valve opening area will be the difference of the port flow area and the valve stem sectional area. The engine utilized in this research does not apply extreme large valve lift, thus the research will omit this condition.

Valve Operation

As the example shown in figure 6.

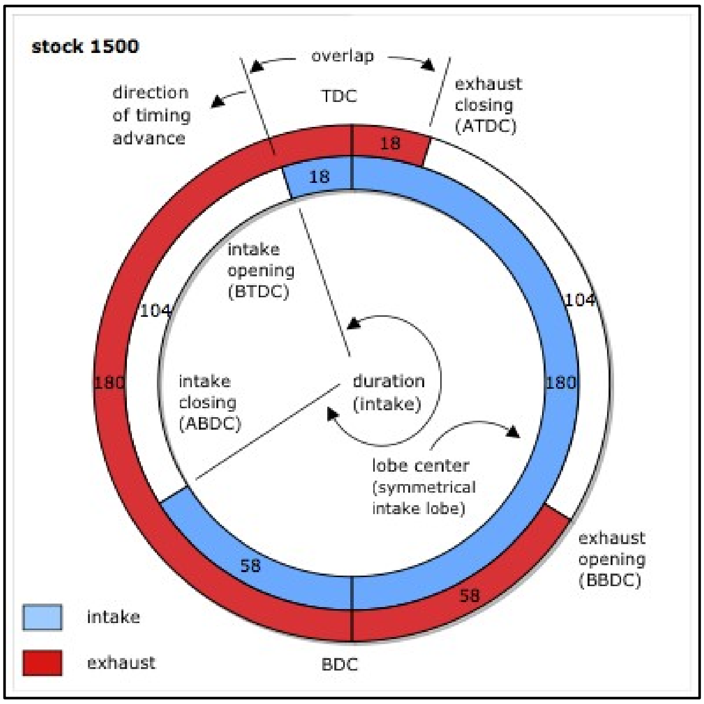

Figure 6: Engine Timing Diagram

Intake valve opening (IVO) occurs in an insensitive timing range of engine performance. For better volumetric efficiency during intake stroke, intake valve usually opens 10° to 20° before top dead center (TDC) where is the highest point that piston can go inside the cylinder. Instead of closing right at the bottom dead center (BDC) where is the lowest point that piston can go inside the cylinder, intake valve closing (IVC) typically retards into the range of 45° to 58° after BDC so the engine has more time to fill the pressure difference between cylinder and intake manifold. Retard intake valve closing helps volumetric efficiency at high engine speed based on air flow inertia and negatively influences it due to back flow which is the condition when gas flows in the opposite direction to the desired direction. Such as the air/fuel mixture flowing out of the cylinder into the intake manifold. Exhaust valve opening (EVO) happens 50° to 60° before BDC. This pre-opening ensures a fully opened exhaust valve during the complete exhaust stroke, which allows a faster exhaust process. Exhaust valve closing appears at 8° to 18° after TDC. In other words, both intake valve and exhaust valve remain opening at the same time for a short period which called valve overlap. At lower speed or idle, it does draw the exhaust back into cylinder due to the intake manifold vacuum. However, at high speed range, late EVC releases the cylinder pressure at TDC and allows an easier intake air flow. In this research, based on the existing Suzuki engine, to control the variations, modification will duplicate all the original engine specifications but focus on the valve configuration.

CHAPTER FIVE. VALVE DESIGN

Being the most popular valve configuration, the conventional poppet valve has operated the gas exchange for internal combustion engines in the last centuries. In order to optimize both the performance and the efficiency of an engine, manufacturers developed multiple more or less complicated subsystems and layouts to achieve the working condition in different situations as ideal as possible. However, the flaws of poppet valve design are not completely solved.

Valve-Piston Interference

With either Overhead Camshaft engine or Pushrod engine, as long as the engine operates with poppet valve, there would be a chance that the piston hits the valve, which called valve-piston interference (figure 3). Especially for a high performance engine which requests a larger intake port and valve lift to keep volumetric efficiency high, the camshaft’s specification is set to be more aggressive, thus the chance of piston-valve interference increases. [20] With the increase of engine revolution speed, the inertia of valve train’s moving parts slow the valve responding speed. Under extreme condition, the valve will be either jumping which causes more wear or floating which affects intake volumetric efficiency and even leads to valve-piston collision.

Most high performance engines, for example, 2008 Honda F22C1 (compression ratio 11.1:1) [21] as well as the ones were discussed previously, 2014 General Motor LS3 (compression ratio 10.7:1) [22] and 2013 Mercedes-Benz M159 (compression ratio 11.3:1) [23], are valve-piston interference engine due to the compromise of higher compression ratio. On the other side, although abandoning high compression ratio does gain the chance to achieve a valve-piston interference free design, the power output from same amount of fuel will be limited and cause a lower thermal efficiency.

Valve Floating

Even though valve-piston interference is avoidable by irregular piston top design and longer cylinder design which keeps the valve further away from the piston, it does compromise compression ratio and the inertia as the inherent physical property is not eliminated. As the explanation discussed in chapter two (pushrod valve), in high revolution speed range, the valve spring does not have sufficient time or rigidity to catch and control the valve which is impacted by either rocker arm or camshaft directly (figure 2, figure 4). The valve will be in the midair and barely has time to run back to complete closing. In this case, the retard of intake valve closing and the intake flow-back occurs. The piston pushes the air/fuel mixture back into the intake manifold and power output will be impaired.

The most popular solution of valve floating is replacing valve springs with much stronger ones. [14] In this case, the valve spring is powerful enough to catch the valve from floating, however, the increase of noise, wear and friction is ineluctable.

In order to neatly eliminate valve-piston interference and reduce the influence of moving parts' inertia, the ideal condition is that nothing goes into the cylinder and nothing moves up and down. Rotary valves emerged, which are located above the cylinder inside of the cylinder head. Without space occupation inside of the cylinder in any condition, piston will never have an opportunity to meet the valve even the timing system is absolutely failed. Its continuous rotation converts linear inertia into rotational inertia, which does not consume any of the power to change the motion direction. However, the existing rotary valves have their limitations unfortunately.

Single Overhead Camshaft

Single Overhead Camshaft (SOHC) is the term to describe the engine that only one camshaft presents to operate both intake valve and exhaust valve at the same time under an inflexible timing order. In a similar configuration, the early rotary valve was machined from a single rotary shaft with both intake and exhaust ports, located inside of the cylinder head. Bishop Rotary Valve is an example of this structure. [2] The configuration in figure 5 is an early SOHC rotary valve design. In the world of the poppet valve, due to the fixed timing set, fundamentally, the engine with SOHC layout valve train cannot reach a satisfactory low fuel consumption thus was abandoned.

Transverse Layout

In the poppet valve engine, for example, an inline four-cylinder dual overhead camshaft engine (figure 7), a column of either intake or exhaust valves will be actuated and controlled by a single camshaft. In this case, all the valves lift up together with the operation of camshaft onto a same height based on the profile of the cam lobe. Due to the fixed specification between the lobes on a single camshaft, the timing between the valves is invariable. The previously explained existing rotary valve locates transversely at the top of the cylinder and operating all of the cylinders together as the poppet valve does.

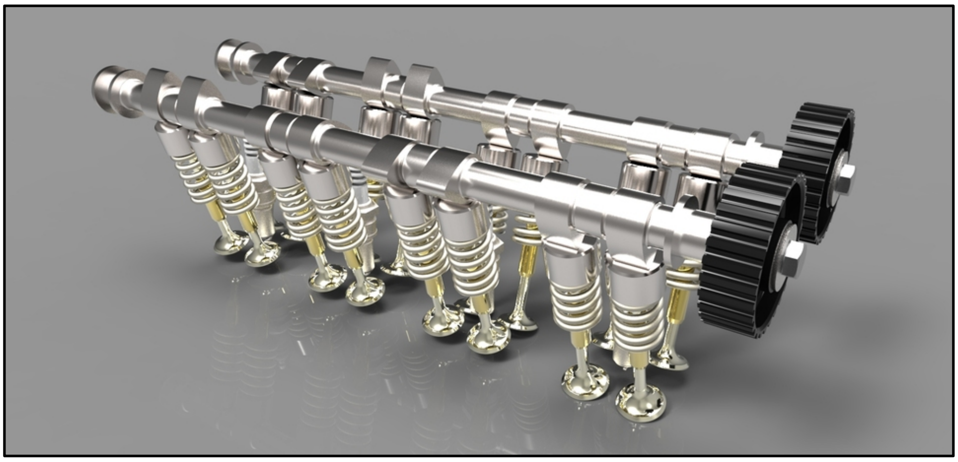

Figure 7: Dual Overhead Camshaft Valve Mechanism Layout

Cylinder Deactivation is an advanced engine cylinder control technology which shuts down a certain number of cylinders momentarily based on engine's working condition decided by engine control module. [24] As shown in figure 8, in a certain cylinder deactivation system, engine control module adjusts engine control strategy by monitoring and analyzing the driving and load condition. Considering the vehicle on the highway or under light load, the engine control unit (ECU) actives an actuator to feed the oil pressure inside of the hydraulic lifter so the lifter will be softened and compressible. In this condition, the camshaft compresses the lifter continuously but the valve remains close. Usually, the engine will be controlled to deactivate one cylinder at the top dead center while another at the bottom dead center to remain both' positive and negative pressure which could be counteracted during the strokes. Fuel injector and spark plug will also be inoperative at the same time. This provides an expected gain of up to 15 percent of increase in the miles per gallon (MPG).

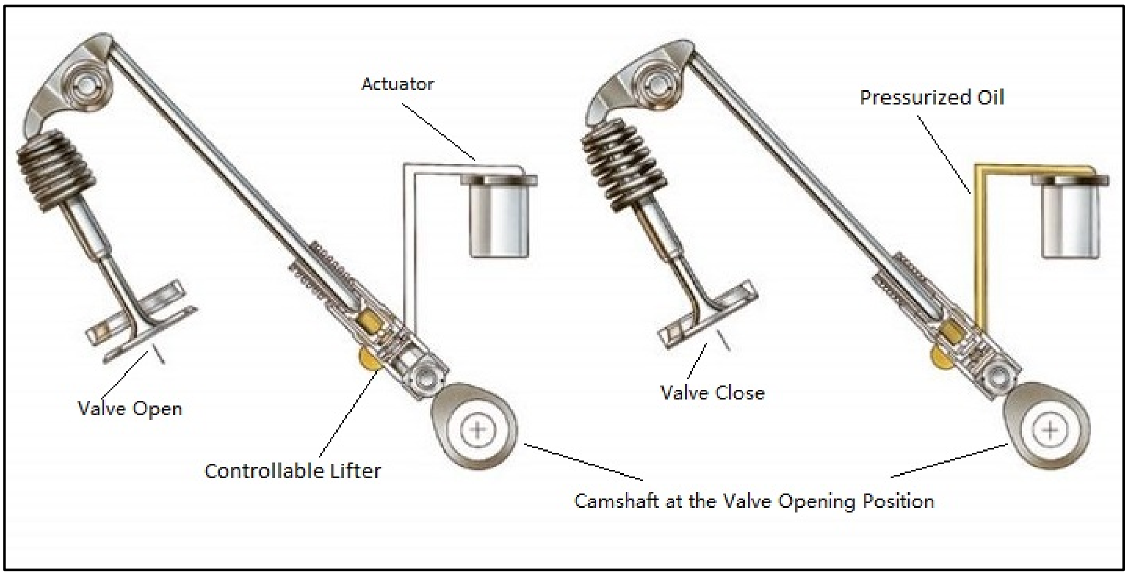

Figure 8: Cylinder Deactivation Technology

Due to the transvers layout of the present rotary valve, however, there is no chance to control the cylinders separately with a solid rotary valve. Especially, cylinder deactivation technology usually requires an even number of cylinder deactivation which ensures the cylinder pressure balance. Thus, deactivating one side of three cylinders on a V-6 engine is unpractical for transverse rotary valve. Figure 9 shows the configuration of transvers rotary valve for inline four-cylinder engine.

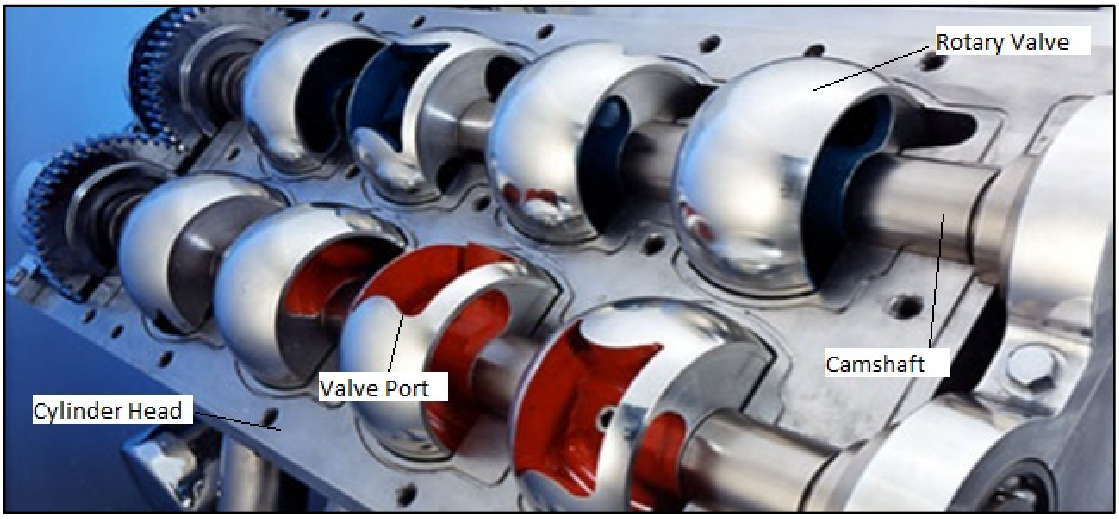

Figure 9: DOHC Transverse Rotary Valve Layout

Erect Rotary Valve

In order to solve the previous discussed problems, an individually installed rotary valve configuration is under discussion. It is desirable that the rotary valves associated with each individual cylinder have the capability to open and close independently to the valves in other cylinders. Being a moving part, the valve, moving either rotationally or reciprocally, needs a power input for each separately for individual control to allow the possibility of Cylinder Deactivation Technology. Thus, the present transverse configuration is no longer practical, in which, valves connect each other into a solid piece. In the meantime, the valve should maintain its latitude without stabbing into the cylinder to eliminate the influence of inertia effect so that valve floating and valve-piston interference will no longer exist.

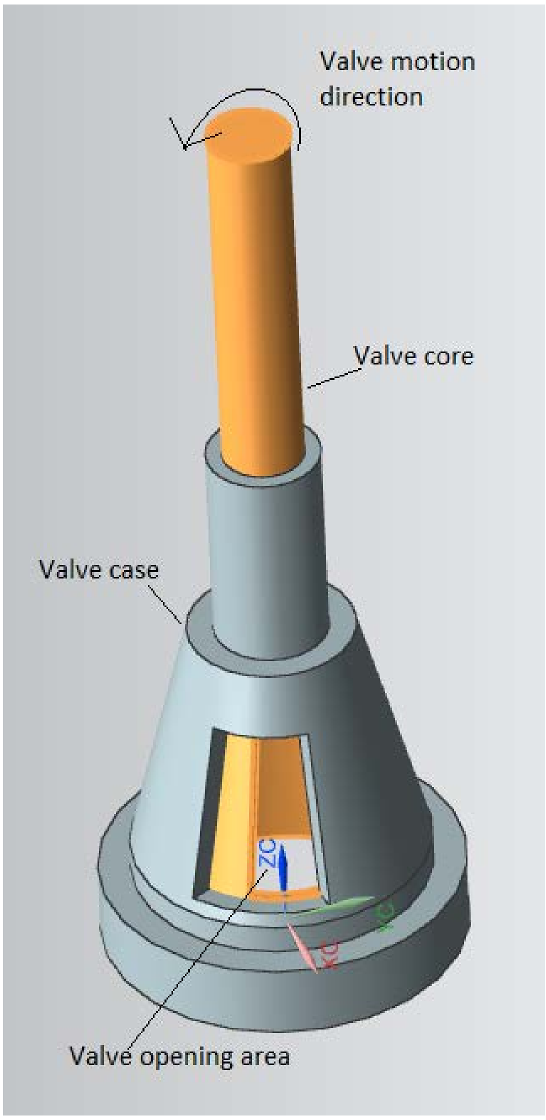

Figure 10: The Erect Rotary Valve

In this research, integrating the advantages of conventional poppet valve and transverse rotary valve without their original imperfections improves engine performance. The Erect Rotary Valve for the modified Suzuki engine will be located above the cylinder inside of the cylinder head at the original position as the poppet valve. As the shown schematic in figure 10, it includes a valve case regarding as the conventional valve seat and its valve core which equals the actual valve. According to the original valve area, a machined open area will be present on both the case and core to be the vent which connects the cylinder to the atmosphere. Instead of moving up and down reciprocally, the valve core rotates continuously inside of the valve case. The vents on both align or stagger based on the timing set regarding to valve opening and closing.

Referencing the conventional poppet valve which will be pushed upward against the valve seat to achieve an airtight seal, the open area on erect rotary valve will be cut at a lower position next to the bottom of the valve and clears the top of center section of the valve core to be a cup shape which holds the pressure during the combustion stroke and pushes the valve core against the valve case. The cone shape walls will be compresed together and the valve will reach an airtight seal mechanically. Its erect positioning separates the driving power input of the valve compared to the transverse rotary valve and provides an opportunity for improvement of the individual valve control mechanism.

CHAPTER SIX. ENGINE PARTS FABRICATION

Cylinder Head Modification

In order to clear the space inside of the cylinder head and its valve cover for the new valve mechanisms, removal of the original poppet valve, valve seat, valve guide, and valve tensioning system (spring and its components) is necessary as well as the original rocker arms and valve clearance adjusting port's caps which are actually the barriers of the erect rotary valve shaft. Since the research was implemented to create an optimum valve system for the existed piston engine, the valve was designed based on the present Suzuki engine structure with minimal possible of engine modification. After removal of poppet valve components, the bare cylinder head is ready to accept Erect Rotary Valve. Figure 11 and figure 12 shows the modified cylinder head and valve cover.

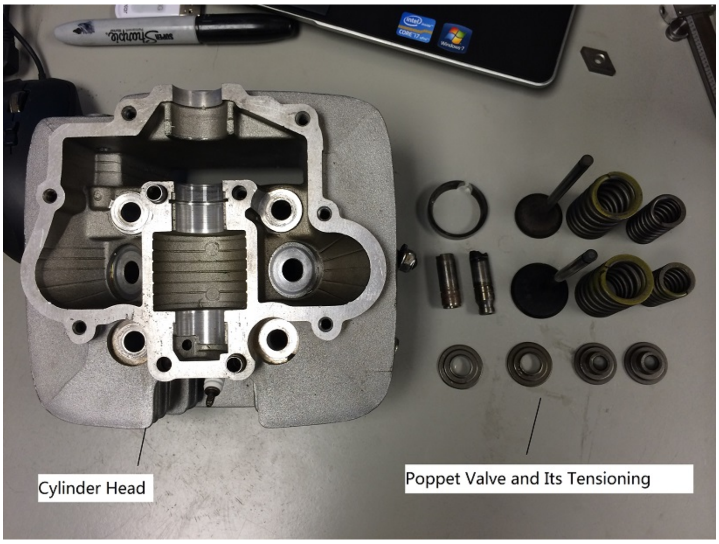

Figure 11: Modified Cylinder Head

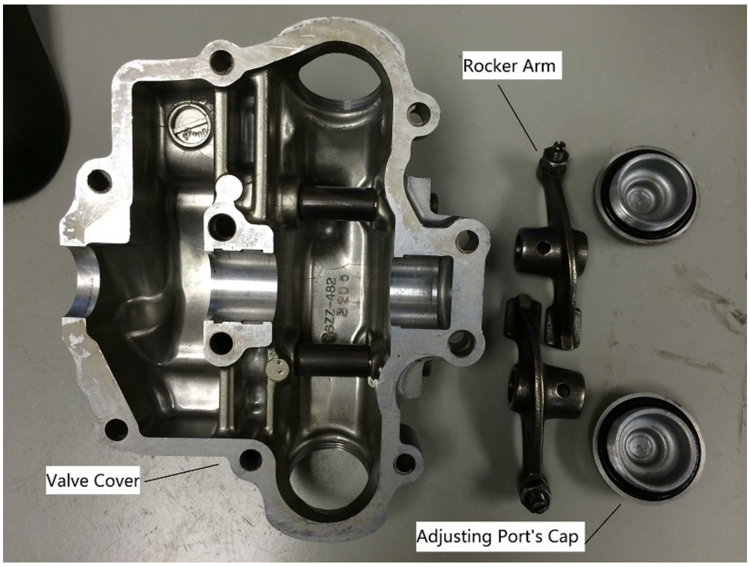

Figure 12: Modified Valve Cover

Camshaft Modification

In this research, the scale of innovative displacement will be focusing on the valve mechanism only, so the timing system is still operational as the power source of the valve. However, in the present Suzuki engine, the timing system ends at the top of the cylinder. In order to lead the power to the valves from the crankshaft. As shown in figure 13, extension of the original camshaft needs to pierce the cylinder head and transfer the power by a sprocket-chain pair to the erect rotary valve driving system located above the engine.

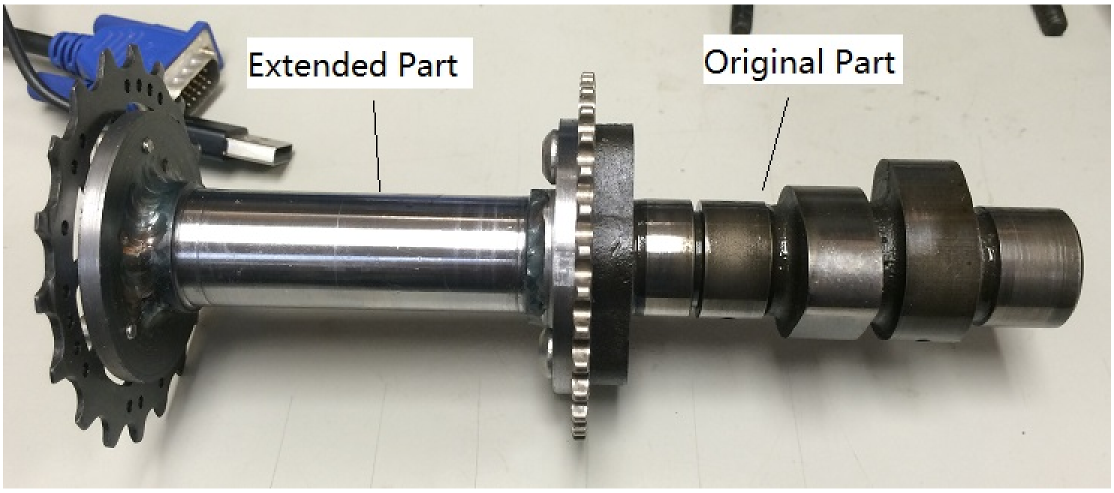

Figure 13: Extended Camshaft

Valve Fabrication

Surface Manufacturing

Briefly explained in the valve design section, the principle of sealing for erect rotary valve is obvious. Since both inner wall of the valve case and outer wall of the valve core will be rubbing against with each other by combustion pressure, similar to the convention poppet valve, a proper lapping of the contacting surfaces is necessary. Valve lapping is the process that describes an engine repairing step which sets the contacting surface for both poppet valve head and valve seat into a same angle. By which way, the poppet valve will maintain a widest contacting surface which blocks pressure leak as much as possible. In reality, there are two familiar methods can complete valve lapping, which are valve seat CNC three-dimension cutting with valve head angle grinder and valve self-grinding technique. In this research, because of the deep cone shape of the erect rotary valve, the specific poppet valve seat CNC three-dimension cutting technology is not practical. On the other hand, according to valve self-grinding technique, the valve core will be grinding against to the valve case with grinding compound in between each other. With rotating either of them, they will be grinded together to remove the flaws attributed of machining marks. Thus, valve self-grinding optimized the final sealing result. Machining by the same lathe which was set to 14° to gain the exact same angle for the contacting surface achieved a good match for both the valve case and valve core.

Figure 14: Finished Contact Surface

As shown in figure 14, after the machining work, differing from the conventional poppet valve which operates admirably after 220-240 grit contacting surface grinding, in order to perform an airtight sealing and frictionless rotating, the contacting walls of the erect rotary valve are needed to be polished to gain the finest surface finish with as low as possible of friction.

Heat Treatment

Treated metal parts will be supplied with a direct (fire furnace) or an indirect (electromagnetic induction heating) energy and subsequently cooled back into room temperature, which called heat treatment. [25] In the process of heat treatment, the furnace slowly heats the metal parts into a uniform temperature where the desired metallurgical microstructural changes occur. Once the furnace reaches the given temperature, the parts are held for a given time to ensure the complete metal crystal conversion. After the holding stage, quenching the parts into the quenching media with a given cooling rate will maintain the desired metallurgical structure. In order to withstand the friction under high pressure, the erect rotary valve needs to be heat treated and furthermore, an additional reinforcement of the contacting surfaces is required.

In this research, considering easier machining work, material price and material availability, low carbon steel was chose to be the primary material for the erect rotary valve. SAE 1018 is a general purpose low carbon steel that contains 0.15-0.20 percent of carbon and well suitable for surface hardening. [26] [27]

In this specific application, the maintained high hardness will withstand the continuous friction. After machining work, the following proper steps will harden the parts. “Carburizing is a process in which austenitized ferrous metal in brought into contact with an environment of sufficient carbon potential to cause absorption of carbon at the surface and, by diffusion, create a carbon concentration gradient between the surface and interior of the metal." [28] Based on SAE 1018 properties, the furnace will heat the parts to 880°C-920°C with carburizing powder which contains charcoal and energizer for four hours. [26] In the four hours carburizing process, the heated parts will be absorbing carbon (charcoal) into the surface to increase the percentage of carbon at the surface. In the following step, the furnace will heat the parts to between 780°C-820°C then quenched in water. [26] Immediately, a 150°C-200°C temper treatment improves the surface toughness with as small as possible effect on hardness. Instead of hardness value of HRC (Rockwell C) 43-45 for non-carburized low carbon steel, an expected hardness value of HRC 58 will be showing for the carburizing result. [29] [30]

Valve Drive Train Fabrication

Customarily, the timing system is located at the front of an engine. Considering what a motorcycle engine is supposed to do, looking at the engine from the front, the crankshaft rotates counterclockwise to power the transmission and the drive chain to the rear wheel. Behind the engine timing cover, the single overhead camshaft will be also spinning counterclockwise driven by the timing chain to push the valves through the rocker arms. Explained previously, in a fixed timing four-stroke engine, the driving ratio between crankshaft and camshaft is 1:2, instead of, every two revolution the crankshaft rotates, the camshaft rotates one revolution (figure 1). This research will modify and reuse the original camshaft, therefore the present mechanism will still determine the crankshaft-valve driving ratio. In other words, every section of the valve train after the cam-sprocket will be set up to 1:1 driving ratio.

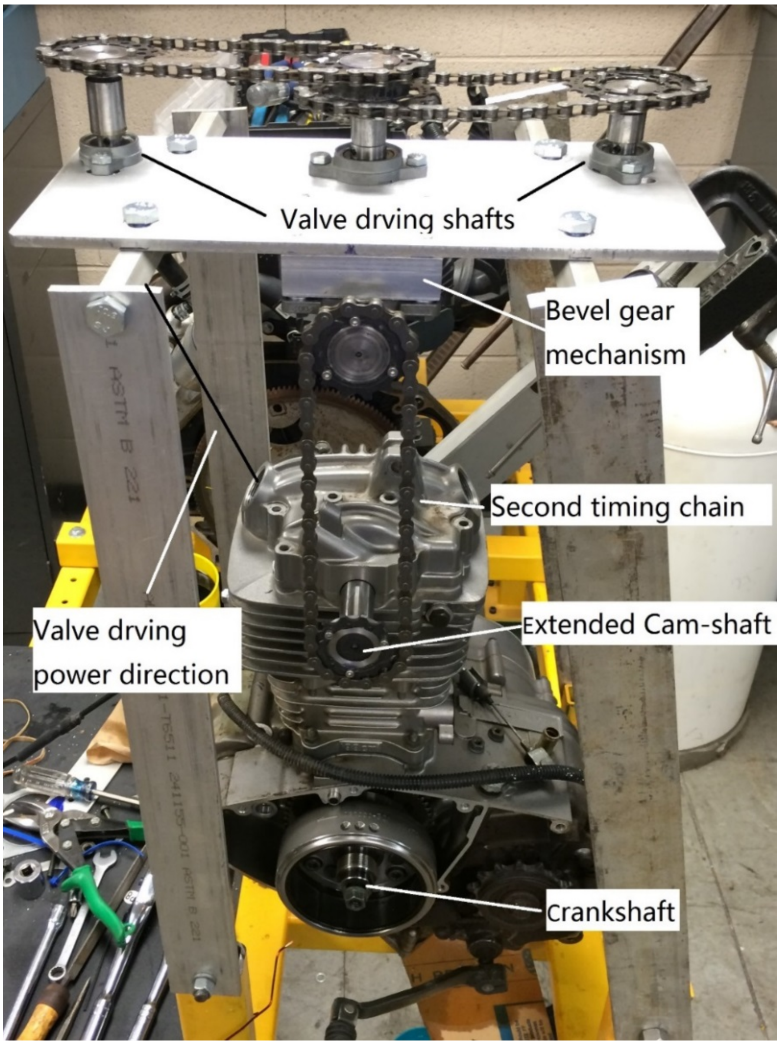

Figure 15: The Erect Rotary Valve Drive Train

According to the erect rotary valve configuration, the valve mechanism will be sitting into the original position of the poppet valve. In this case, the power input direction of the erect rotary valve will be erect to the cylinder head top (figure 15). A valve driving platform is required, which will be sitting above the cylinder head. Figure 15 shows the entire valve train and its power transferring direction.

According to the assembly diagram, with rotation of the crankshaft, the extended camshaft converts driving speed to 2:1 ratio and transfer power to the external timing sprocket. Transited through the sprocket-chain pair at the front of the engine, power will be lead to the bevel gear pair. Theoretically, the main task of the erect rotary is exchanging the gases between cylinder and atmosphere so the actual valve can be set to spin either clockwise or counterclockwise. However, in reality, the driving mechanism will connect the valve core through the thread pair. The best way to spin, thus, will be the tightening direction of the thread pair.

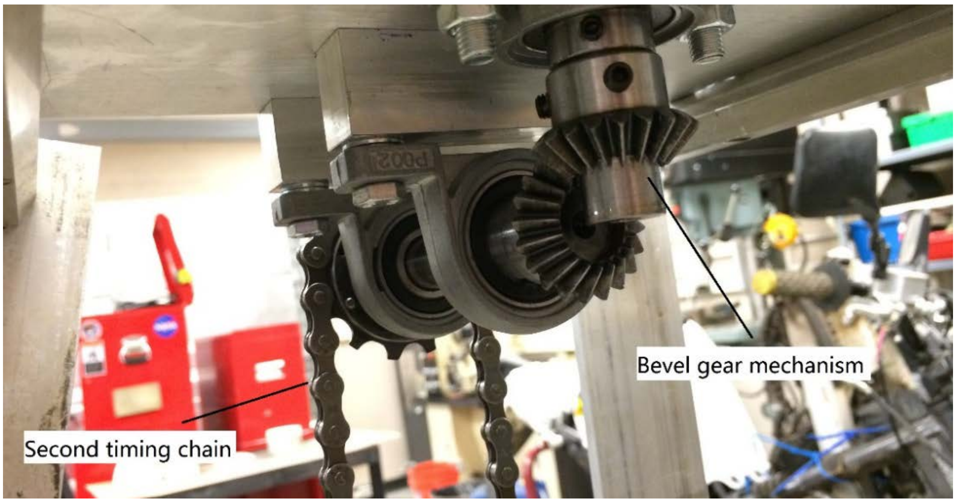

Figure 16: Bevel Gear Mechanism

In this case, assembly of the bevel gear pair needs to be in the rotary direction figure 16 shows, vertically. The shaft that sits at the center section of the platform is the actual camshaft for the modified Suzuki engine, which transfer power to the intake valve shaft (right) and the exhaust valve shaft (left) to drive the erect rotary valve. (Figure 15)

Timing Setting

According to the timing diagram that is shown in figure 6 and the valve operation principle that was discussed in chapter four (valve operation), timing setting can be addressed down to the angles where the valves open or close.

In this typical engine:

Intake valve opening occurs at exact TDC.

Intake valve closing occurs at 27° after BDC.

Exhaust valve opening occurs at 21° before BDC.

Exhaust valve closing occurs at TDC.

Camshaft Related Parameter Setting

Lift and duration air the most primary parameters for the design of camshaft, which determine how high and how long the valve lifts during the operation of the engine. Figure 17 shows the diagram of camshaft cross section.

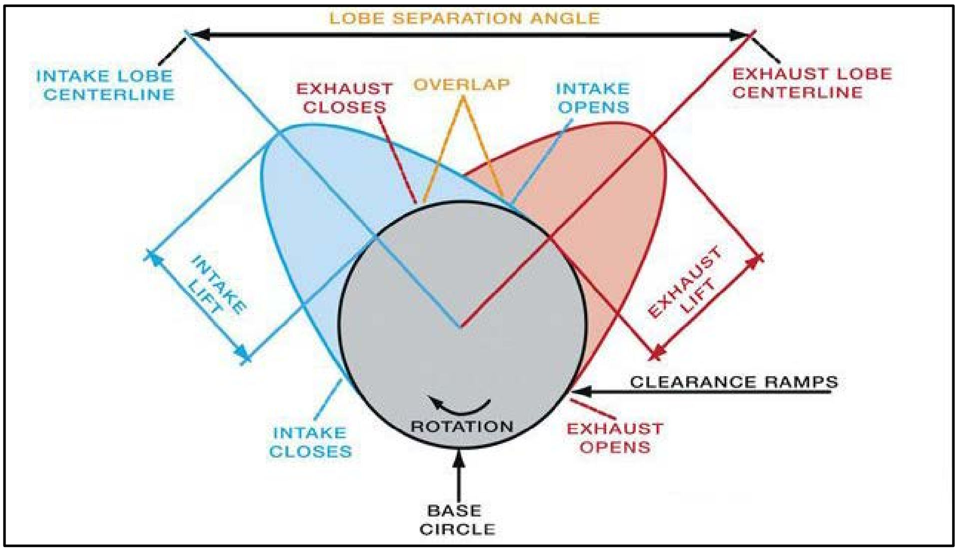

Figure 17: Camshaft Cross Section Diagram

Base Circle

The base circle is the round portion on the camshaft lobe, in which, the valve will be remaining closed. In this research, the original camshaft lobes have no function thus the base circle is no longer critical. The original camshaft base circle is 1.1 in..

Lift

Camshaft lift is the maximum distance that the lobe pushes the valve lifter, which relates to the valve area. To calculate it, lift equals to difference between the maximum size of the lobe and the minimum size of the lobe (base circle). Sometimes, the rocker arm will multiple the valve lift from camshaft lift. In the experiment, the valve opening area will be sitting directly into the valve rotary contacting walls according to the original valve lift. The original valve lift equals to the camshaft lift times the rocker arm increasing ratio.

In the Suzuki engine, the camshaft lobe's maximum sizes are 1.341 in. (intake) and 1.27 in. (exhaust) and the lifts are thus 0.241 in. (intake) and 0.227 in. (exhaust). The measured magnifications for both rock arms are 1.335. The intake and the exhaust valve lifts are 0.322 in. (intake) and 0.303 in. (exhaust), respectively.

Valve Opening Area

Discussed in chapter four (valve opening area), valve area equals the product of valve lift and valve head circumference. According to the original poppet valve parameter, the valve head diameters for the intake and the exhaust are 1.3 in. and 1.1 in., respectively. The valve opening area for both are thus 1.314 sq.in. (intake) and 1.047 sq.in. (exhaust).

Duration

Duration is determined by the length of time that the valve is open, which is measured in crankshaft rotation degree. Duration is measured from the time the valve is at a 0.050 in. lift on both open and close. Therefore, total duration occurs when the valve is open at 0.050 in. to 0.050 in. from closing. In this application, intake valve duration is 117° and exhaust valve duration is 111°.

Setting of Erect Rotary Valve

Due to the inherent property of the camshaft lobe, a smooth transition between the base circle and the lift portion is necessary. This causes a gradual valve opening and closing, which means the valve cannot lift to the maximum opening area in a short time. And this is also the reason why the poppet duration is measured between

0.050 in. after the opening and 0.050 in. before the closing. The duration in this range is the effective valve lift. Figure 18 and figure 19 show the measured valve lift curves. According to the curves, maximum valve lift for intake valve and exhaust valve are 0.322 in. and 0.303 in. respectively, which match the calculated results.

One of the advantages of the erect rotary valve is providing a sharp opening and closing and linear valve lift curve. In reality, besides focusing on the valve opening area, the true objective of valve improvement is the quantity of air aspirated into the cylinder, which is closely related to volumetric efficiency. In this research, all the parameters will be kept the same regarding the original design including the gas exchange capacity of the valve.

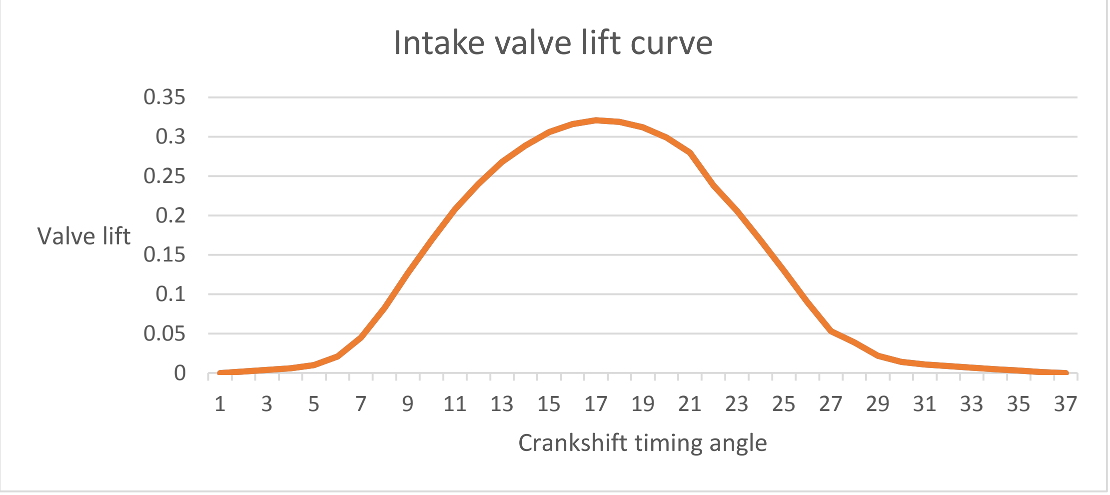

Figure 18: Intake Valve Lift Curve (Poppet Valve)

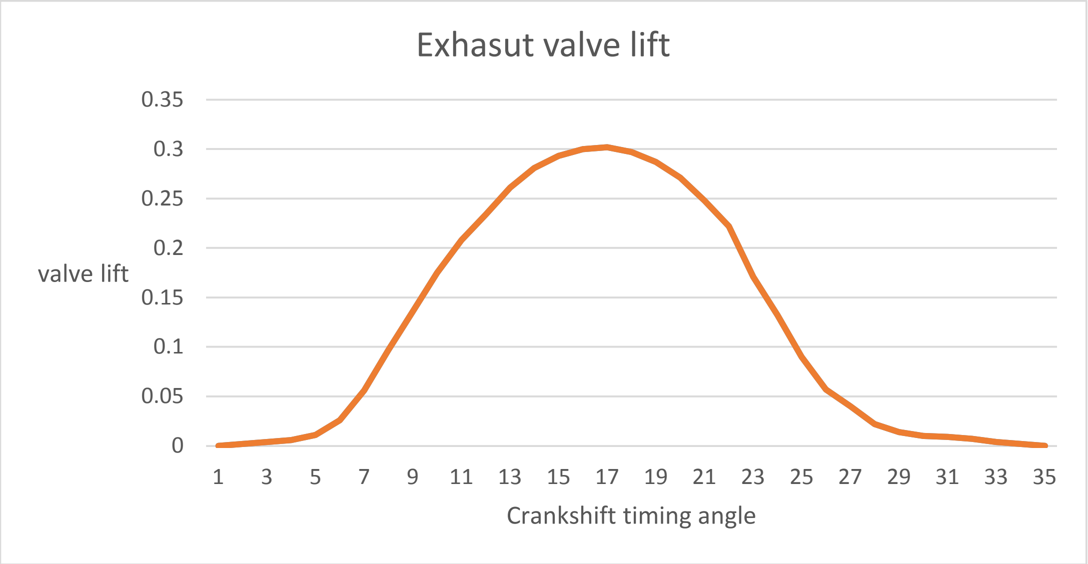

Figure 19: Exhaust Valve Lift Curve (Poppet Valve)

Thus, in order to match design, the valve lift curves are converted into the valve opening area curves through the equation that introduced in chapter four (valve opening area). And the area that covered by valve opening area curve is numerically considered as the gas exchange capacity coefficient. Calculated by MATLAB, the intake exchange capacity coefficient is 18.8642 and the exhaust exchange capacity coefficient is 14.7644. Figure 20 and figure 21 show the valve opening area curves generated by MATLAB.

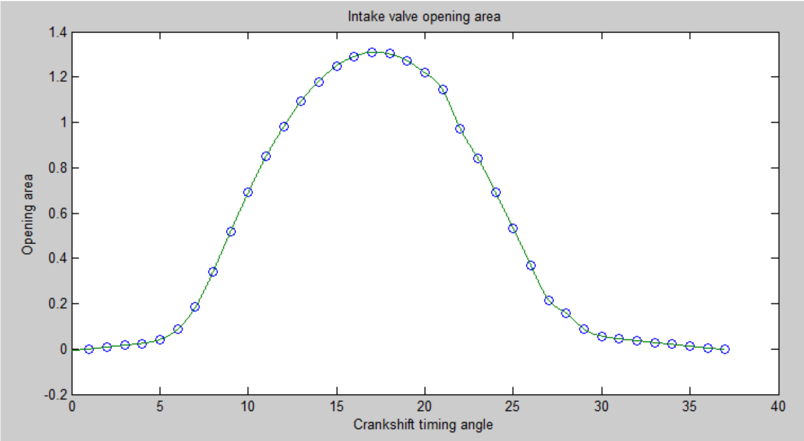

Figure 20: Intake Valve Opening Area Curve (Poppet Valve)

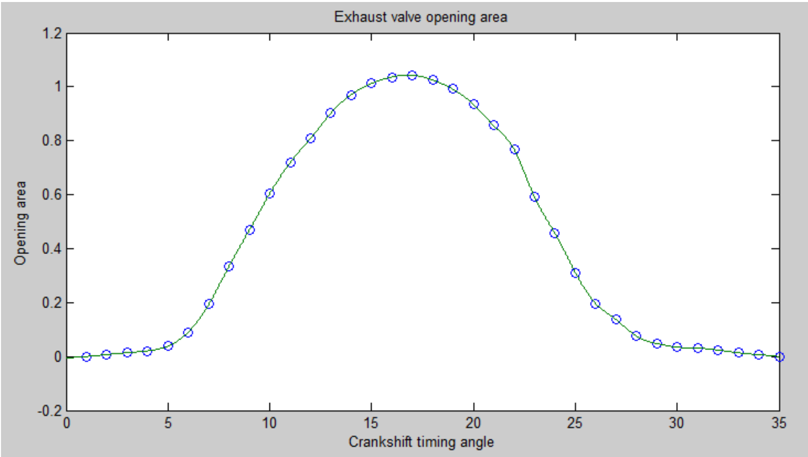

Figure 21: Exhaust Valve Opening Area Curve (Poppet Valve)

Instead of focusing on only the range of effective valve lift, the curve counts from the very beginning of the valve opening to the very last of the valve closing, which covers the entire mass of the air that exchanged by the valve. Since the erect rotary provides a sharp valve opening and closing, the smooth transition is no longer existed. The engine will complete the entire gas exchange within the original effective duration. Figure 22 and figure 23 show the erect rotary valve opening area curves.

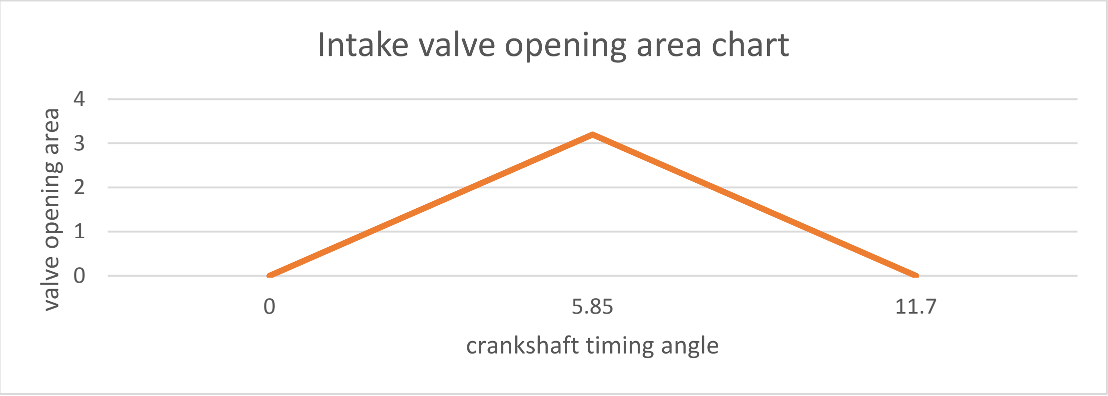

Figure 22: Intake Valve Opening Area Curve (Erect Rotary Valve)

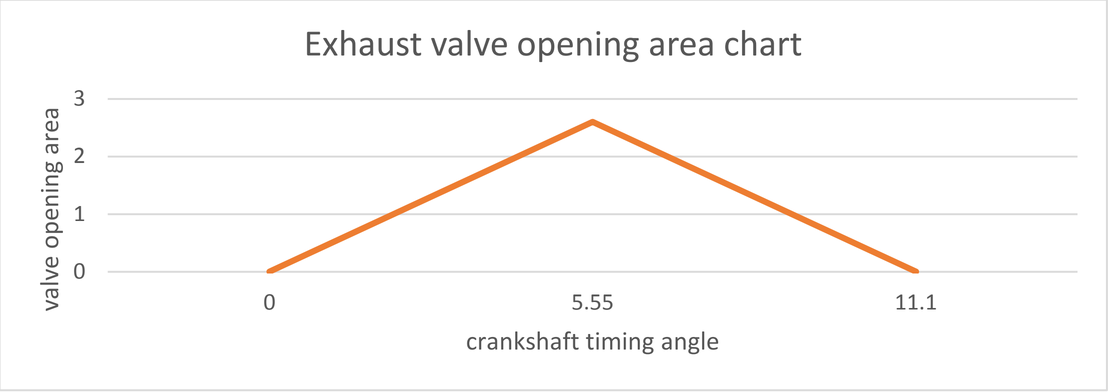

Figure 23: Exhaust Valve Opening Area Curve (Erect Rotary Valve)

Actual Parameter for the Erect Rotary Valve

According to the previous calculation and discussion, the following parameters are set.

Intake valve opening: TDC.

Intake valve closing: 27° after BDC.

Intake valve duration: 117°.

Intake valve opening area: 3.2 sq.in. .

Exhaust valve opening: 21° before BDC.

Exhaust valve closing: TDC.

Exhaust valve duration: 111°.

Exhaust valve opening area: 2.6 sq.in. .

In this research, the calculated size of the erect rotary valve does not fit to the original poppet valve ports because of the limitations of the modified original cylinder head' parameter. To continue the research and corroborate the feasibility of the erect rotary valve as a new valve configuration, some performance compromises are necessary. Thus, the actual erect rotary valve opening areas are set to 1 sq.in. and 0.8 sq.in. for the intake valve and the exhaust valve respectively.

CHAPTER SEVEN. TEST

Erect Rotary Valve Components Contact Surface Hardness Test

Limited by experiment equipment, it is impossible that test the inner contact surface of erect rotary valve case. In this certain condition, a test sample replacement is required. According to the specification of the valve case and the valve core, a flat test sample from the same material (SAE 1018 steel) and the same thickness as the wall of the valve parts is heat treated. In the process of the heat treatment experiment, the sample will treated under the same condition as the valve parts. The resulted surface will maintain the same quality from various aspects such as, metallurgical structure, chemical composition and physical property.

The Rockwell hardness test is a relatively non-destructive, inexpensive and convenient method that empirically tests metal according to a small indentation in the material. [31] The principle of Rockwell indentation test is that the Rockwell machine applies two levels of force to form the indentation and calculate the Rockwell C value based on the indentation depth difference between the two levels of force through a certain equation.

Result: Rockwell test to the sample showed a 60 HRC which meets the expected value.

Compression Test

The core element of an internal combustion engine is the combustion stroke when the spark ignites the fuel to convert the chemical energy into the mechanical energy that is utilizable for the actual automobile. Since the combustion occurs inside the engine, to gain as much power as possible from the expanding combustion gases, the cylinder has to remain a proper seal. [32] A leaking cylinder will cause various problem such as, low power output, rough running and even non-starting. Commonly known, piston rings seal the engine cylinder, in addition to valves, spark plug and/or direct fuel injector. In this research, the only factor that was changed and may cause sealing problems is the erect rotary valve. Thus, a proper cylinder compression test is necessary to measure and appraise the sealing performance of the erect rotary valve.

CHAPTER EIGHT. CONCLUSION

This study is an analysis of the valve system of internal combustion engines. Concentrating on the elimination of the flaws that kept remaining for centuries in the conventional poppet valve, the research provides a feasibility and a direction for the valve train development. Sitting above the cylinder with its rotating motion, the valve and the piston will be running without encounter. Solving the valve-piston interference problem, the engine parameters can be set to be more aggressive and extreme high compression ratio will be coming true. Without the transition portion on the camshaft lobe, the erect rotary valve offers an ultra-sharp opening and closing which allows the valve opening area to be the largest size as soon as possible, and increase the volumetric efficiency. The positioning of the valve clears the interference between the valves with each other with individual valve driving power input. The control of the valve timing will be flexible with involving an advanced electronic control system.

However, the current design of the erect rotary valve does have its limitations. For example, the biggest problem of the current design is the valve opening area. Due to the fixed timing system (timing chain and the valve driving platform), besides the conventional poppet valve that has a ring shape 360° valve opening area, the erect rotary valve only has one directional opening area that aligns or staggers for opening and closing at a certain degree of angle. This dramatically restricts the size of the valve opening area and will cause an insufficiency of gases exchange. The engine performance will be less than the one with the original poppet. Moreover, the dome shape combustion chamber sets the original valves to a certain angle which is an irreconcilable barrier for the positioning of the erect rotary valve which needs to get its power input from the top.

Going through the research and analyzing the problems dependently, consider some possible future developments.

Future Improvement

Variety of Material

An expected HRC 58 carburizing hardened SAE 1018 steel is still not capable enough to withstand the friction under high temperature (950℃ when combustion occurs) and high pressure (300-1000 psi various according to loading condition).

Advanced alloy and ceramic are reliable under extreme loading condition and working environment.

Ball Shape Valve

Contributed by the curve of the sphere contacting surface, the size of the area will be larger than the one in the cone contacting surface within a same longitude and latitude. In this case, with keeping all the parameters, the size of the valve opening area will be larger. On the other hand, with keeping the size of the valve opening area, the valve opening area can be located much closer to the bottom of the valve core, thus, a larger cup shape in the center section of the rotary valve will be remained to hold more combustion pressure.

According to force analysis of the erect rotary valve that has been finished in this research, every time the combustion occurs, the valve core will be pushed against to the valve case, due to its cone shape, the valve will be sealed properly, however, the valve core contacting surface will be stressed by both the force vertical to the surface and the pushing friction to the surface at the same time. In this condition, with the valve spinning, more rotary friction is presupposed which involves higher possibility to seize the rotary valve.

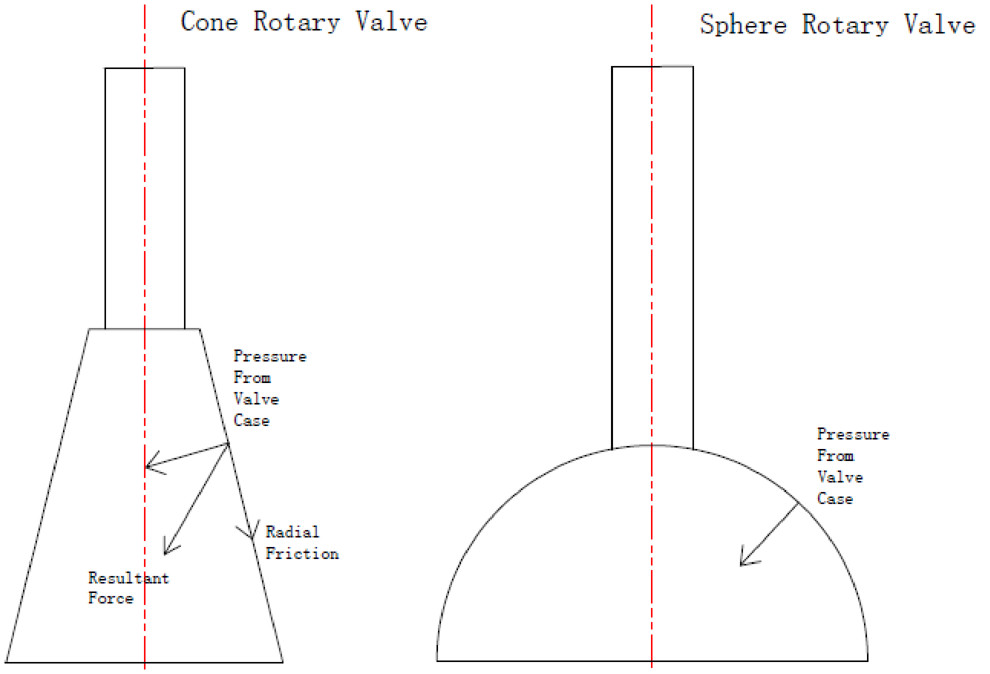

Figure 24: Force Analysis Diagram

As mentioned previously, circle is a perfect pattern in nature, and ball is the extreme of a circle. Configuring the erect rotary valve into a sphere contacting surface, the force layout evenly surrounds the ball shape surface. Thus, the radial friction will not exist. Figure 24 shows the force analysis diagram for both cone rotary valve and sphere rotary valve.

Camless

In a Camless engine just as its name implies, the engine runs without a camshaft. Camless engine is the term that is practical to describe a special type of poppet valve engine. Due to the advanced electric control technology, the conventional timing system are no longer necessary for valve operation. Substituting for the timing chain/belt, tensioner/pulley, camshaft and valve spring, the piezoelectric-hydraulic actuator operates the entire system by monitoring the crankshaft position. [33] On the erect rotary valve engine, the concept of the camshaft is dimmed, instead of, the valve events are controlled by the valve vent area and its angle. Compared to the poppet valve Camless configuration, which requires pressurized oil feed, both piezoelectric and hydraulic actuators, the rotary valve can be easily be driven by electric motor and achieve up to a certain accuracy with advanced control strategy. Friction loss is eliminated from the entire valve train.

Multi-Vent Valve

Differing from the conventional poppet that provides a 360° ring shape opening area, the timing system limits the recent concept of the erect rotary valve to be directional ventilation, thus only can open and close at one direction which dramatically restricts the valve opening area size. Moreover, the present timing system is an actual barrier for more advanced variable valve control technology, which follows the generic four-stroke engine cycle. In other words, the present erect rotary valve will also rotate one revolution for every two revolution that the crankshaft spins, due to the fixed timing set by the timing chain system. However, driven by the expected electric valve control system, more than one vent in the valve core is feasible. In this case, for example, the valve has two vents that provide an overall larger valve opening area, the electric motor will only need to rotate the valve for 90° for every 4-stroke. The revolution speed and cycle reduce dramatically. The wear and the requirement of electric motor are lower too.

Accomplishments and Future Direction

An innovative new valve configuration for an internal combustion engine is demonstrated during the process of this research, which addresses the problems and limitations combined with the conventional camshaft driven poppet valve system. In the past decades, a variety of rotary valve technologies to improve the performance and properties for the poppet valve are suggested, but none have realized wide acceptance. The Erect Rotary Valve developed by this research is a new achievement that not previously discussed. The poppet valve's problems that caused by inertia, valve-piston interference, limitations on volumetric efficiency, and lack of valve actuation flexibility are addressed by an innovative valve system that is potentially possible to be greatly improved on the performance in an internal combustion engine. The demonstrate engine for the test of the new Erect Rotary Valve proved to not be ideal due to its inherent design of the cylinder head. A newly designed cylinder head would be a better approach for the Erect Rotary Valve specifically. This research has demonstrated the feasibility of the new valve configuration and has introduced insight into how to improve the performance for future designs. For example, the introduction of a hemisphere shape valve will obsolete the present 14 degree cone shape valve. As any research project would answer questions and raise more at the same time. However, the Erect Rotary Valve design is a fresh technological improvement to internal combustion engine and merits additional research and development.

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