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Research Article

Design, Modeling, and Feasibility Analysis of Rotary Valve for Internal Combustion Engine

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There have been several studies focused on improving the efficiency of internal combustion engines using various techniques such as better design, better materials, and regenerative technologies. Recently, in 2016, Toyota reported 40% gas engine efficiency with their Prius model; however, there remains a lot more room for improvement towards the theoretical maximum value of 73% using the Carnot theorem. In this research, we present a freshly designed valvetrain that has the potential to improve the efficiency of a known conventional valve designed engine. The goal of this research was to prove the feasibility and significance of the new valve design. This research developed a simulation model of the new valve design and produced its physical property data. The data of the new design were compared to the conventional poppet valve design with respect to several parameters to discuss its working principle and advantages over the conventional valve mechanism. Modeling was performed using Python programming to predict the valve-opening mechanism. The design of experiments was setup to control and tune different parameters accordingly within the reasonable range of engine speed, viz., 1000–6000 rpm to simulate various working conditions. The maximum opening area for the rotary valve is calculated to be 0.795 sq.in which is smaller than the poppet valve's area of 1.315 sq.in. However, under an example of 2900 rpm, the rotary valve was able to remain fully opened with constant efficiency of about 54% from 40 to 160 degrees of the crankshaft angle. While the poppet valve can achieve 88% efficiency at 90 degrees of the crankshaft angle and the efficiency significantly drops on either side of the maxima, the authors believe that this research would help explore improvements in the performance of a combustion cycle due to the novel rotary valve design that is investigated in this paper.

1. Literature Review and Introduction

Recent advancements in design of internal combustion engines have made a lot of progress towards improvement in thermal and mechanical efficiencies of the engine as well as resulting in higher mileage and range of the vehicle. Valve design has evolved over the decades due to constant demand of highly efficient and high-power automobiles with 6+ cylinders. The valve opening area and timing are some of the most critical parameters to achieve high efficiency. The transverse rotary valve is the most direct conversion to the original piston internal combustion engine due to the structural similarity to the conventional poppet valve configuration. This section will demonstrate the research progress that has been reported in the literature, followed by the challenges facing the conventional poppet valve design and the advantages of rotary valve design.

Chow, Watson, and Wallis have conducted a study about combustion in a high-speed rotary valve spark-ignition engine. In this research, they designed the combustion model that can simulate a combustion performance for a transverse rotary valve engine with up to 18000 revolutions per minute (rpm) of engine speed. The experiment data indicate the paths to engine combustion process improvements. According to their study, engine power output increases with volumetric efficiency and in-cylinder velocity, with respect to RPM, contributes to the engine power output with its increase [1]. Bishop Innovations published their work in 2007 with a dual port single rotary valve design. In their research, a string of timing gears was applied to replace

timing chain/belt to transfer the power from the crankshaft to the rotary valve. Integrating both intake and exhaust ports into a single column-shaped valve body, the Bishop rotary valve maximizes the port size and occupies most space above the cylinder for gas exchange. The rotational motion removes the inertia from the conventional reciprocating poppet valve. To form a proper seal, similar to a piston ring, a seal sits around the rotary valve vent and is slightly preloaded to push against the contacting surface. The developer states a 16 kg weight reduction with their rotary valve when building a 3-liter V10 F1 engine comparing to the engine that has the poppet valve. The research also indicated that performance remains the same with their rotary conversion and the peak volumetric efficiency is the same as well. The dual port single valve was successful on F1 racing cars from 1995 to 2005 in reaching 20000 to 24000 rpm [1].

In 2015, Boretti and Scalzo optimized the pneumatic poppet valve. In the study, they also designed a rotary valve which provides ultrasharp valve opening and closing. According to the research, a rotary valve has its capacity to improve the volumetric efficiency by providing the largest valve area in a short time. Their experiment sets the compression ratio up to 14 : 1. The achievement of their rotary valve includes higher power density, better engine breathing properties, higher fuel conversion efficiency, and weight reduction [2]. Boretti's other research also indicated that rotary valve could provide a chance for the engine to gain a higher compression ratio. The study included Bishop Innovations' achievement that solved gas sealing, oil sealing, excessive friction, and seizure caused by thermal and mechanical distortion. The research also indicated that the gas flow will be different from the poppet valve engine due to the lack of piston top valve clearance pockets. Muroki et al. published their work in 1999 focusing on the flow dynamic and the friction effect. The study proves that rotary valve can save up to 40 percent on valve driving mechanical loss. However, the notch profile in the early stage of the intake stroke would affect the intake flow [3]. Muzakkir et al. also conducted a study in 2015 with a hypothesized erect rotary valve that works with a magneto-rheological fluid instead of a solid metal valve seat to form a proper seal and prevent wearing out. However, none has fabricated and tested this configuration of rotary valve [4].

Brown et al. introduced a set of floating valve seal system, in which the spring will push the floating valve seal against the rotary valve to form a seal and self-adjusts to accommodate the wearing out. In the study, the rotary valve was fitted to the high-speed pneumatic machine [5]. In 2014, Zibani et al. designed, tested, and implemented a rotary valve control unit for a single-cylinder engine. The study addressed problems of the conventional valve-equipped engine, such as piston-valve interference and the complexities of the poppet valvetrain. They proposed a software-operated electronically controlled rotary valve (ECRV) which manages the system and offers fully flexible valve event control. According to the study, the throttle body can be eliminated to reduce pumping loss. Since the engine control unit successfully operated the experimental system, the idea of extending the electronically controlled rotary valve into a multicylinder engine was shown feasible. The feature of the electric rotary valve also provides the possibility for variable timing control [6]. An analysis presented by Tsu showed an operation with intake and exhaust valve overlap. He implemented a program based on the mathematical modeling to estimate engine performance. The predicted results fitted mostly well to the experimental data that were collected from three different engine examples [7].

Theobald et al. fitted a new programmable electromagnetic valve actuator on a single-cylinder research engine to explore efficiency and emission improvements with variable valve actuation operation. Research only shows a net-efficiency gain under certain condition. However, actuator's electrical input energy loss was less than the friction loss for a conventional valvetrain [8]. In 2017, Stone et al. fitted an electric motor actuated valvetrain on a Jaguar Land Rover 4-cylinder engine and was able to gain up to 7.5 percent of fuel economy improvement. The study also confirmed throttleless operation feasibility [9]. In 2019, Myers introduced a novel engine head design with a new rotary valve system. The study indicates the new design helps volumetric efficiency and cylinder flow. With the new design, the combustion process takes place more evenly and consistently. The disk shape valve rotor design does not provide any mechanical sealing ability and requires two radial seals which mimic the side seals in a Wankel engine. However, Wankel engine side seal was not an optimum solution to its own. The valve rotors are interconnected; hence, there is limitation in variable valve timing [10].

Mu et al. published their research in 2022 about improving engine thermal efficiency. According to the experiment, the research engine DAM16N achieves its minimum fuel consumption when the engine is running between 2000 and 2800 rpm [11]. In 2015, Kopac and Kokturk observed the optimum engine speed. Their study presented both experimental measurements and analytical modeling throughout a wide range of engine speed. 2580 rpm was found to be the best running point for the specific engine [12].

1.1. Benchmark Engine Model. In this research, an engine from a 1996 SUZUKI DR200 motorcycle that is 4-stroke, spark-ignited, timing chain driven dual-overhead-camshaft, and gasoline fuel powered was selected as the benchmark which provides the base data for all parameters. The improvements are also developed and compared based on the selected engine structure.

1.2. Shortcomings in Conventional Valvetrain. In order to accomplish gas exchange throughout the entire process combustion, the engine has to have a series of intake and exhaust valve movements based on a timing setup. Conventionally, the valves are driven by the engine crankshaft with a series of mechanical transition systems. The entire system between the crankshaft and the valve is called the valvetrain. On the mass produced engines, the valvetrain can be classified into two basic categories which are pushrod driving and belt driving, while in the belt driving category,

timing belt and timing chain are applied for different demands. There have been several challenges identified in the literature for the conventional valvetrain such as inertia, friction, timing, and duration. These challenges are explained in detail as follows [13].

2. Valve Interference

Based on the operation of a four-stroke engine, calculation shows that at 4000 revolutions per minute (RPM), a valve will open 2000 times every minute which converts to 33 times a second. Due to the inertia, a heavy valvetrain will keep its motion further until valve spring catches it. Eventually, under higher RPM, the valve and its components will be struck too far to be caught by the valve spring in time. Valve floating and valve-piston interference occur [14].

According to Trzesniowski, conventional valve springs are capable to support up to 16000 rpm without causing valve floating. However, such a system requires a much complex valvetrain concept [15].

2.1. Power Consumption. Usually, varying between different engines and valvetrain configurations, the valvetrain contributes up to 25 percent of the total internal friction. This percentage reduces with the increase in engine speed. For example, in the study of valvetrain friction [16], the members of Automobili Lamborghini, Calabretta, and Cacciatore introduced that based on motored strip measurements, valvetrain contributes 35 percent of total engine components' friction at 1000 rpm which is close to the engine speed range of crawling in slow traffic and cursing on highway [14].

This percentage can be very significant especially if the valve spring needs to fight harder to eliminate valve floating in high performance engines. Youd identifies better valve spring dynamic performance with higher internal stresses [17] Valve floating is mainly caused by resonances in the valve springs. To solve this, up to two additional springs can be sleeved up inside of one other. A ribbon damper is also an alternative. However, according to Youd's research, dampers can generate heat and will lead to much higher power consumption [17].

2.2. Valve Timing, Lift, and Duration. The conventional valvetrain, either driven by the pushrod or the belt, has to have a valve actuator known as the camshaft. Figure 1 shows the structure of the camshaft. On the camshaft, for each valve, there is a cam lobe designed following the specification of the valve opening duration, lift, and timing. In other words, the valve motion is preset and controlled by the shape, height, and angle of the cam lobe. However, in order to accommodate different working conditions and achieve the optimum efficiency, the valve timing, lift, and duration need to have a considerable amount of variation range [13].

To relatively widen the optimum efficiency range, auto manufactures and researchers sought various routes on modifying the very basic conventional valvetrain. Fluid actuated valve systems were quite popular in late 1990s and early 2000s. Renault and Aprilia both created the pneumatic valve actuator system to increase valve opening speed and closing force. Renault later also created an electric hydraulic valve actuation system that allows for more advanced valve timing [19].

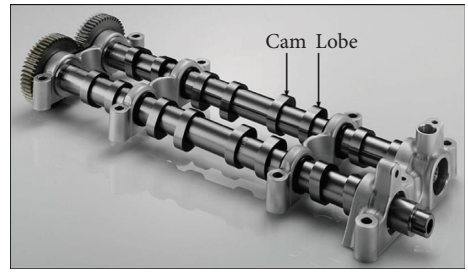

Figure 1: Camshaft structure [18].

However, rarely any fluid valve actuation system made to the market. More popularly, manufactures prefer the desmodromic valve actuating system. They are indeed more reliable and however introduce even more mechanical parts.

Hence, a novel valvetrain, electronic rotary valve, was created to eliminate the potential of the valve floating and the valvetrain friction by changing the motion type of the valve and reducing the amount of components driven by the crank shaft. Ultimately, cooperating with wider range of variation, the improvement of the engine efficiency should be achieved overall during the entire power band. The advantages of a rotary valve over a conventional poppet valve have been reported in research [20–22] and can be summarized as (1) elimination of reciprocating valve motion can result in reducing frictional power losses of the engine. (2) Optimized combustion chambers can be designed using a rotary valve that will provide high discharge coefficient maximizing the airflow in the combustion chamber. (3) Rotary valve can have larger cross-sectional area for an equivalent sized poppet valve. (4) Increased engine power and reduction in fuel consumption can be achieved by eliminating preignition conditions seen in conventional poppet valve. (5) Fewer moving parts in the rotary valve design would result in the reduced costs of manufacturing and maintenance.

The new valve will be fitted into the original spaces for the conventional valve. Driven by the overhead electric motor, the valve spins in place to open and close by staggering the vents in the side. Figure 2 shows the novel rotary valve assembly configuration.

3. Design and Modeling

3.1. Valve Opening Timing. According to the timing diagram that is shown in Figure 3, timing can be addressed down to the crank shaft angles where the valves open or close.

On the selected benchmark engine, the intake valve opens at exact TDC and then closes at 207° after BDC. The exhaust valve opens at 201° before BDC and then closes at exact TDC.

3.2. Camshaft Related Parameter. Lift and duration are the most primary parameters of the camshaft, which determine how high and how long the valve lifts during the operation of the engine. Figure 4 shows the diagram of the camshaft cross section.

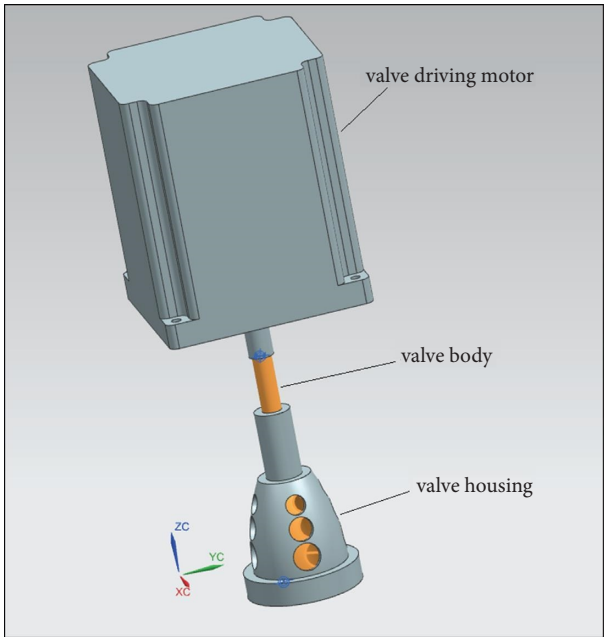

Figure 2: Rotary valve assembly configuration.

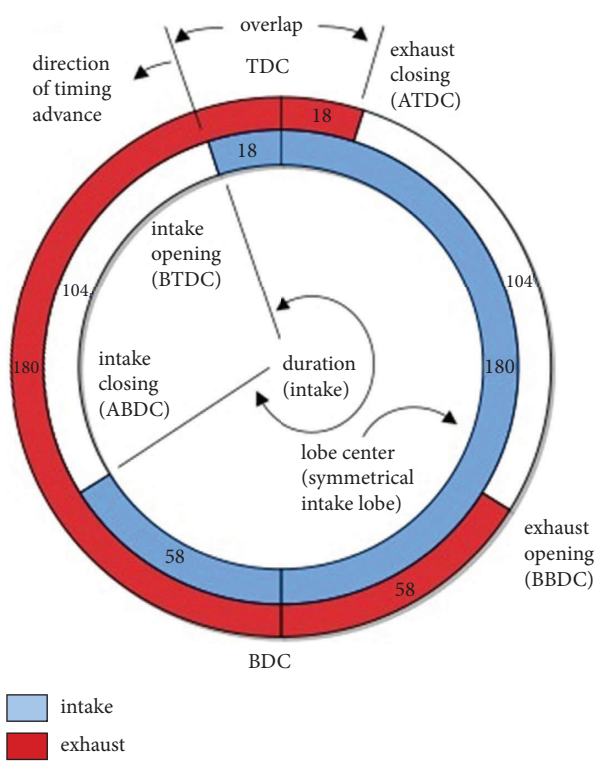

Figure 3: Engine timing diagram [23].

3.3. Lift. Valve lift refers to the maximum distance covered by the valve during the opening process. This measurement is determined by calculating the disparity between the maximum height of the cam lobe and the size of the cam lobe base circle. Occasionally, the valve lift can be magnified by the rocker arm, which amplifies the height of the camshaft

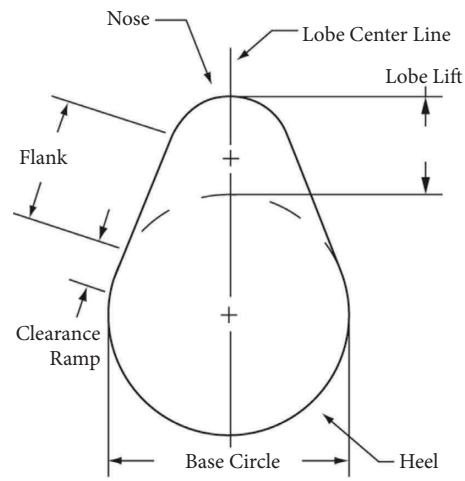

Figure 4: Cam lobe diagram [24].

lobe. In the context of this study, the initial valve lift is equivalent to the maximum lift of the cam lobe multiplied by the rocker arm's augmentation ratio.

$$l = l_l r_a. \tag{1}$$

Here, l stands for the valve lift, while l_l and r_a represent the lobe lift and the rocker arm ratio.

On the benchmark 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 [14].

3.4. Valve Opening Area. The valve opening area is determined as the curtain area by multiplying the valve lift and the circumference of the valve head, within the critical condition. According to measurements of the original poppet valves, the valve head diameters for the intake and exhaust are 1.3 inches and 1.1 inches, respectively. Consequently, the valve opening areas for the intake and exhaust valves are 1.314 square inches and 1.047 square inches, respectively. While when the curtain area is equal to the valve port area, the valve opening area is considered as the port area.

3.5. Duration. The duration of valve opening is determined by the period the valve remains open, and it is measured in the crankshaft angle. This duration is assessed from when the valve is lifted 0.050 inches to when it is 0.050 inches away from complete closure. In this particular scenario, the intake valve duration is 207°, while the exhaust valve duration is 201°.

To ensure a smooth rotation of the camshaft lobe and proper valve operation, a transition from the base circle to the maximum lift height is essential. Consequently, the valve's motion is gradual, especially at the beginning and end of its movement. This study concentrates on the performance of the intake valve, so only the intake side will be

examined. Figure 5 illustrates the measured valve lift curve, indicating a maximum valve lift of 0.322 inches for the intake valve, aligning with the calculated results.

3.6. Requirements of the New Valve Design. To prove that a new design is significant, at least the original valve performance has to be met. Under this circumstance, the gas exchange capacity is the key factor of the performance. In other words, matching design of the gas exchange capacity becomes the goal of the research.

The rotary valve offers a notable advantage by delivering a sharp and linear valve motion curve. While the physical port of the valve may not reach its original area, the primary goal of valve improvement extends beyond the emphasis on the valve opening area. The true objective is to enhance the quantity of air aspirated into the cylinder, a factor intricately linked to volumetric efficiency.

In contrast to the traditional valve motion, where attention is typically confined to the effective valve lifting range, a more comprehensive approach considers the entire span from the initiation to the culmination of the valve motion. This broader perspective encompasses the entire mass of air exchanged by the valve. Unlike the conventional valve, which experiences a wasteful duration during the ineffective valve lifting range due to its smooth transition, the rotary valve is specifically designed to facilitate a sharp and precise valve opening and closing. Consequently, the smooth transition characteristic is eliminated in the rotary valve design.

4. Design Details

4.1. Timing and Duration. Ultimately, the new design has the ability to achieve unlimited timing and duration variation. However, in this research, since the goal was set to match design on the benchmark engine, the timing and duration settings remain as the original engine measurement.

4.2. Lift and Valve Opening Area. The rotary valve operates on engine speed-related rotational stagger motion, so the term lift is no longer applicable. However, the shape of the opening port does contribute to performance variation. Thus, the lift can be replaced as opening and closing duration which describes the speed of valve operation.

As discussed, one feature that the rotary valve provides is the sharp valve motion curve which can be translated into fast valve motion. The feature provides the engine a wider range of effective gas exchange duration.

4.3. Valve Shape. In order to accommodate the original Suzuki engine cylinder head, the valves have to fit into the space of $1.386 \times 1.386 \times 2.2$ inches for the intake valve, respectively. The optimum shape of the valve application is hemisphere which evenly distributes the force between the valve body and its housing under the combustion cycle. Limited by the size of the space, however, the valves are finalized into a cone shape with curved surface to prevent self-seizing under heavy load.

On this typical design, the opening ports are made into true circles with three different sizes to accommodate the shape of the valve. The sizes are set to 0.119, 0.148, and 0.165 inches' radius.

4.4. Driving Mechanism. Instead of using the traditional timing components, the rotary valve is driven by the overhead steeper motor. With timing trigger wheel mounted on the crankshaft and correlated crankshaft position sensor, the engine control unit will be able to sense the exact angle of the crankshaft and trigger the steeper motor to drive the valve accordingly to time the motion.

5. Simulation

5.1. Method. In order to identify the improvement of the performance on the new valve design over the conventional valve, several parameters can be applied as the measurement. In this research, the shape of the valve body and its port are modified and hence the motion type. One major change that resulted is the volumetric efficiency. On the internal combustion engine, higher volumetric efficiency allows the air to flow easier. In other words, the cylinder is able to aspirate more air within the same crank rotation angle.

Since the major change of the structure is the valve shape and motion type, the most direct result will be the change of the valve opening area curve. Thus, in this research, instead of focusing on the overall volumetric efficiency table, the individual efficiency curve for one cycle of the valve motion will be presented. Comparing this curve between the new design and the conventional design, one can easily identify the difference of the performance.

5.2. Program Design. Volumetric efficiency is the ratio of the actual aspirated air volume and the physical cylinder volume.

$$\mu = \frac{V_a}{V_d}, \tag{2}$$

where V_a stands for the actual volume of intake air, while V_d represents the theoretical volume of the cylinder [25].

The benchmark engine is an indirect-fuel-injection engine. However, since the amount of fuel is small enough compared with the amount of air, the fuel mass can be neglected for volumetric efficiency calculation [26].

In equation (3), the actual intake air volume can be presented as the function of air mass and air density.

$$V_a = \frac{m_a}{\rho_a}. \tag{3}$$

On the engine dynamometer, air mass is usually replaced by the intake air mass flow rate [26].

$$\dot{m}_a = \frac{m_a N_e}{n_r}, \tag{4}$$

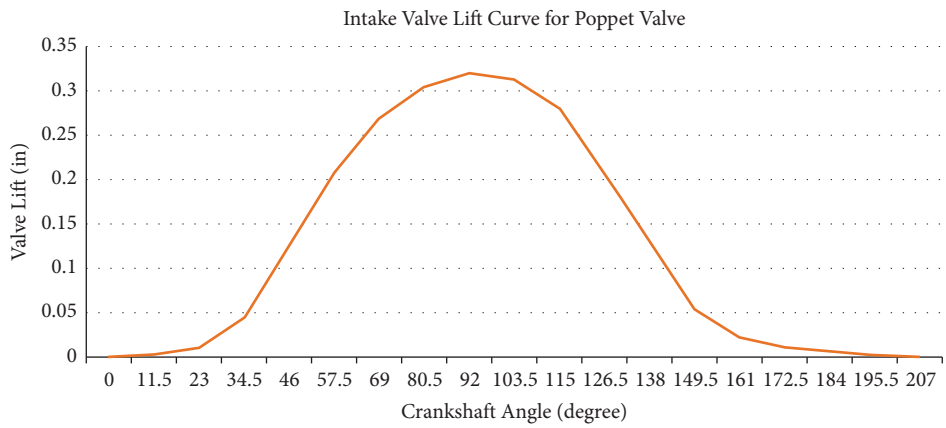

Figure 5: Poppet valve lift height curve.

where N_e stands for engine speed and n_r is the number of crankshaft rotations for a complete engine cycle.

Intake air pressure and temperature are usually measured in the intake manifold, so the intake air density can be calculated as the following equation:

$$\rho_a = \frac{P_a}{R_a T_a}, \tag{5}$$

where ρ_a is intake air density, P_a is intake air pressure, T_a is intake air temperature, and R_a is gas constant for dry air.

Replacing 4 and 5 in 3 gives the volumetric efficiency equal with the following equation:

$$\mu = \frac{\dot{m}_a n_r R_a T_a}{P_a V_d N_e}. \tag{6}$$

In this research, the major change of the improved design as compared to the benchmark engine is the valve shape and its motion type. As the result, the valve flow and discharge coefficients are the most essential effects of the volumetric efficiency. Thus, only the intake performance will be evaluated [27].

The mass flow rate through a valve is usually described by the equation of compressible flow going through a flow restriction.

$$\dot{m} = \rho_o c_o A_E \left(\frac{P_T}{P_O}\right)^{1/k} \left\{\frac{2}{k-1}\left[1-\left(\frac{P_T}{P_O}\right)^{k-1/k}\right]\right\}^{1/2}, \tag{7}$$

where P_o and ρ_o stand for upstream stagnation pressure and density, respectively. $c_o = \sqrt{kRT_o}$ stands for sound speed with T_o standing for temperature. A_E is the effective area of the valve assembly. P_T represents downstream static pressure [28].

For flowing into the cylinder, P_o and P_T are the intake system pressure and the cylinder pressure, respectively.

Introducing equation (7) into equation (6) and keeping the valve opening area A_E as the variable, the relationship between the valve opening area and the instant volumetric efficiency can be described.

5.3. Valve Opening Area. Figure 6 shows the design of the rotary valve. In the new design, linear motion no longer exists and hence the curtain shape opening port. The valve has three differently sized round ports in every 90 degrees. Driven by the electric motor, for every 45 degrees of rotation, the valve completes its opening and closing. In order to perform a proper curve of the opening area change, the three ports in a roll have to open and close at the exact same time.

In order to calculate the effective valve opening area and present the motion curve, the system can be simplified into the area problem of a line sweeping across a circle as shown in Figure 7. In this case, the valve opening area can be described as the sum of the truncated circle areas.

$$A_0 = \arccos\left\{\frac{r-d_o}{r}r^2 - \left(\sqrt{r^2-(r-d_o)^2}\,(r-d_o)\right)\right\}, \tag{8}$$

where r stands for valve port radius.

Since the valve housing and core both have the same size port, the effective valve opening area should be twice as the circular section area.

$$A = 2(A_{01} + A_{02} + A_{03}). \tag{9}$$

d_o, in equation (8), represents the linear distance traveled by the valve ports. A_{01}, A_{02}, and A_{03} represent the A_0 of the 3 port holes, respectively. In this research, since the variable valve algorism is not introduced, the valve motion and the crankshaft rotation angle are still considered as related.

$$d_0 = \frac{\theta v_v \pi R}{360 N_e}, \tag{10}$$

where v_v and R represent the valve rotation speed and radius of the valve port orbital.

To complete the comparison between the new design and the old design, the same curve of the conventional valve is needed too.

Based on the valve shape and its motion type, poppet valve has a circular cap that moves up and down to modulate the valve opening and closing. During the valve opening, the edge of the circular valve draws a cylindrical curtain shape and the area of the curtain is the instantaneous valve area [25].

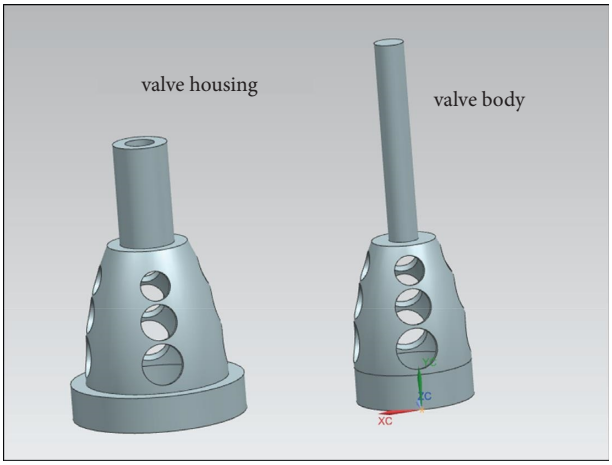

Figure 6: Rotary valve.

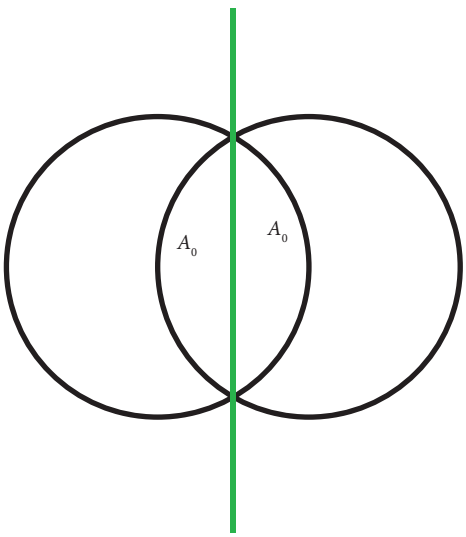

Figure 7: Simplified valve opening problem.

$$A = \pi d_v l, \tag{11}$$

where d_v and l represent the valve diameter and the valve lift. Both parameters are obtained from the actual measurement. By applying the data points of valve lift to the method of polynomial approximation, the valve lift to the function of crankshaft angle can be obtained. Tables 1 and 2 show the coefficients of the 14-degree and 15-degree polynomial approximation.

5.4. Saturation Point. At somewhere in the midrange of the valve lift, the saturation point of the port will be achieved. After this point, the valve curtain area goes beyond the size of the valve seat area and the flow restriction moves from the valve curtain to the actual port itself.

At this point, the valve opening area becomes the valve seat area.

$$\mathrm{A} = \pi r^2. \tag{12}$$

5.5. Discharge and Flow Coefficient. The effective valve opening area defines the mass flow rate though the valve, which is the product of the reference valve area and the valve discharge or flow coefficient.

For the conventional valve structure, the discharge coefficient will be applied if the reference valve area is set to be the curtain area. Otherwise, the flow coefficient becomes applicable if the reference valve area is the seat area. In this research, the flow coefficient was adopted through polynomial approximation of GT-power simulation [25].

$$\begin{aligned} A_E &= CA_r, \\ C_f &= -0.001 + 3.5477\frac{l}{d} - 6.566\left(\frac{l}{d}\right)^2. \end{aligned} \tag{13}$$

While on the new rotary valve design, since the valve opening area is determined only by the opening condition, equation (9), critical condition is no longer necessary to be considered. We only need to determine the flow coefficient.

The conventional numerical simulated equations are no longer applicable. However, since the structure of the valve opening ports is shaped into circles, the equations of the nozzle and orifice flow coefficient become suitable for this application.

The nozzle or orifice was used to reduce pressure. In this case, however, it became the restriction of the air flow.

$$C_d = C_\infty + \frac{b}{R_e^{\,n}}. \tag{14}$$

Referencing the physical design of the rotary valve, the device type can be identified as "orifice, corner taps." The discharge coefficient is defined as the above equation, where C_∞ stands for the discharge coefficient at infinite Reynolds number, β stands for the area ratio, R_e stands for the Reynolds number, and b and n are the coefficients found in the chart from reference [29].

$$\begin{aligned} C_\infty &= 0.5959 + 0.0312\beta^{2.1} - 0.184\beta^6, \\ b &= 91.70\beta^{2.5}, n = 0.75. \end{aligned} \tag{15}$$

6. Results and Discussion

6.1. Valve Opening Size. Since the conventional poppet valve operates related to the camshaft rotation angle, the valve opening area curve should remain invariable under any engine speed. Figure 8 shows the intake valve opening area curve of the poppet valve.

However, the rotary valve is designed to be driven by the electric motor under the motor's constant speed. Once the valve completes its opening operation, the motor will stop and keep the valve remaining opened and then drive the valve close per command of the engine control unit. Limited by the size, it is expected that the new valve design provides a smaller opening area. Nevertheless, the valve opening duration will be increased. Figure 9 shows the valve opening area curve of the rotary valve in three dimensions. According

Table 1: 14-degree polynomial approximation coefficients of the poppet valve lift curve.

$1.34057576152852e-29$	$-1.97553920205812e-26$	$1.46162855199868e-23$
$-7.37941269758326e-21$	$2.74879288704423e-18$	$-7.49437859202936e-16$
$1.45815618211744e-13$	$-1.97909977340450e-11$	$1.82797615744295e-09$
$-1.10629478732787e-07$	$4.10232387967087e-06$	$-8.27649925543051e-05$
0.000792266345094215	−0.00231720481869556	0.000147178187343951

Table 2: 15-degree polynomial approximation coefficients of the poppet valve lift curve.

$8.72448957224518e-30$	$-1.35313642804956e-26$	$9.45434850116815e-24$
$-3.93036276539530e-21$	$1.08112500700193e-18$	$-2.06876504858949e-16$
$2.81579223001290e-14$	$-2.73591172698436e-12$	$1.87301430848427e-10$
$-8.74677136652550e-09$	$2.62475776957364e-07$	$-4.57848868734980e-06$
$4.04649013154706e-05$	−0.000135047970803517	0.000360469542360491
$4.54797548741340e-05$		

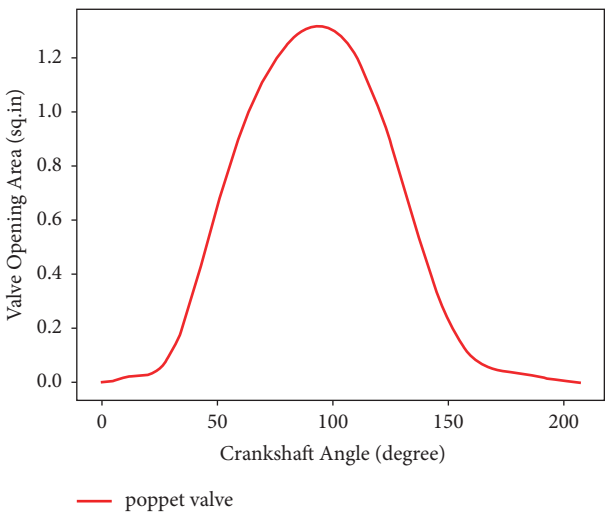

Figure 8: Intake valve opening area curve for the poppet valve.

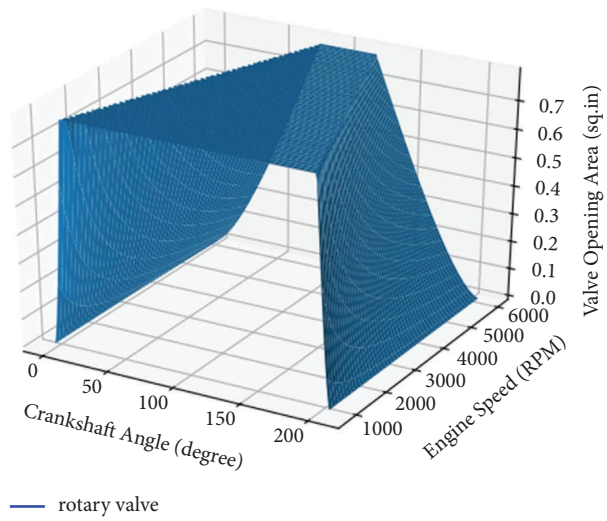

Figure 9: Intake valve opening area curve for the rotary valve.

to the calculation, the maximum opening area for the rotary valve and the poppet valve are 0.795 sq.in and 1.315 sq.in.

Since the valve operation speed remains constant, with the engine speed increasing, it is obvious that the maximum valve opening area duration reduces. Eventually, the electric motor will not be able to catch up with the engine speed and the valve will not be able to reach its maximum opening area.

6.2. Volumetric Efficiency. Instead of focusing on the overall valve assembly efficiency, this research went in more detail and calculated the instantaneous efficiency during the valve opening process.

Limited by the motion type and cam lobe profile, the conventional poppet valve has to open and close gradually before reaching the maximum efficiency. In another words, during the beginning and the end of the motion, the valve has to run under a very inefficient condition and can barely aspirate any air. Furthermore, due to the fixed timing system, the poppet valve can only remain in its higher efficiency for a relatively narrow range. However, on the rotary valve design, depending on how quick the valve motor operates, the rotary valve may be able to complete its maximum area opening within a smaller crankshaft angle interval. Figure 10 shows both the instant efficiency curve of the poppet valve and the rotary valve at the engine speed of 2900 rpm.

However, due to the performance limitation of the valve driving motor, the valve may not be able to reach its maximum efficiency. With the engine speed increasing, the time interval of the intake stroke reduces. Since the valve driving motor operates under its specified speed, the engine control unit may have to command the valve to start to close before the maximum opening area completes. According to the calculation, the rotary valve design and the conventional poppet valve design will achieve very similar performance at 4400 rpm. Then, after 4500 rpm, the poppet valve performance exceeds. Figure 11 shows the efficiency curve at 4400 rpm. Aspirated air volume ratios between the popped valve and the rotary valve are 0.850 and 0.996 at 2900 rpm and 4400 rpm, respectively.

As mentioned earlier, the maximum opening area for the rotary valve was calculated to be 0.795 sq.in which was smaller than the poppet valve's area of 1.315 sq.in. However, under 2900 rpm engine speed, the rotary valve was able to remain fully opened with constant efficiency of about 54%

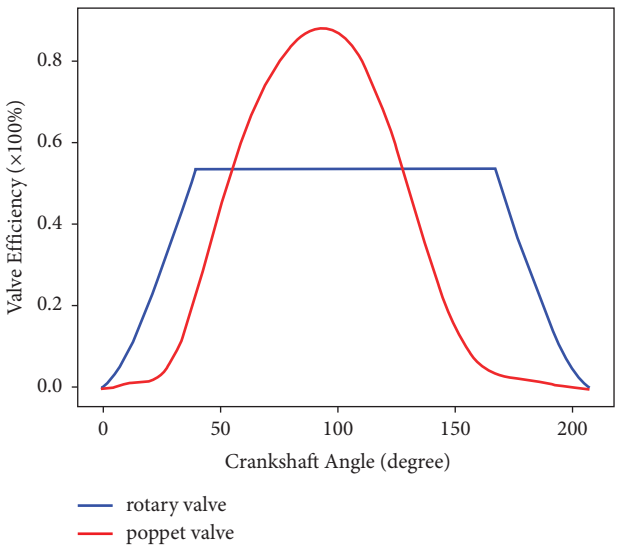

Figure 10: Instant efficiency curve under 2900 rpm.

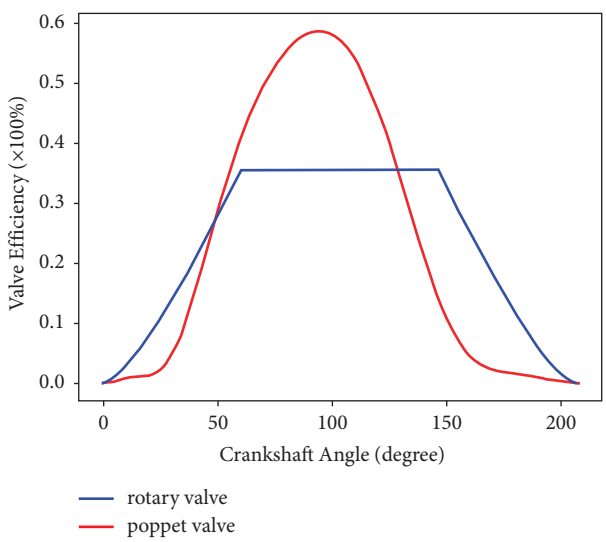

Figure 11: Instant efficiency curve under 4400 rpm.

from 40 to 160 degrees of the crankshaft angle. While the poppet valve can achieve 88% efficiency at 90 degrees of the crankshaft angle, the efficiency significantly drops on either sides of the maxima.

7. Conclusion

Based on the modeling, simulation, and design of experiments, the authors have distinguished the advantages and the limitations of the newly proposed rotary valve design. This design enables maximum opening of the valve for longer duration and hence has the potential to enhance efficiency of the engine. However, in this research, limited by the space, the new design that was constructed based on the existing engine head could not compete on the maximum opening area with the conventional design.

Modifications that make horsepower and torque in the lower rpm range between 1500 and 3000 rpm are way more useful than a high-revving race motor, and most modern civilians use vehicles running at 2000–3000 rpm when cruising at a speed of 70 mph. Literature review also showed that engines obtain their optimum efficiency at lower engine speed. In this research, the authors found that the proposed rotary valve design provides a constant efficiency of 54% for much larger crankshaft angle duration as compared to the conventional poppet valve design under 2900 rpm engine speed.

Based on the calculations, the rotary valve design can achieve better performance below 4500 rpm, and it will contribute towards reduction of the engine internal friction by eliminating the entire valve driving mechanism. Comparing to other rotary valve designs, the proposed design in this study offers a shape that is naturally mechanically sealed. The intake and the exhaust side valves are independent. Electronic control concept offers a fast opening speed and longer duration. The concept is also significant for the future research on the wide-range variable valve timing system and high-compression interference free engine design.

Data Availability

All of the data generated in this article belong to Middle Tennessee State University and can be made available upon request following the MTSU policy.

Disclosure

The authors would like to acknowledge that some part of the initial research in this paper has been previously published as a master's thesis of the first author; the link is as follows: https://mtsu.edu.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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