The Effect of Compression Ratio by Different Piston Head Shape on the Performance of Motorcycle Engine

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ABSTRACT

The compression ratio has a significant impact on engine power, fuel economy, emission, and other performances of internal combustion engines. Basic engine theory states that a higher compression ratio produces higher torque and horsepower. One way of having different compression ratio is by changing piston head shape. A piston is a cylindrical engine component that slides back and forth in the cylinder bore via forces produced during the combustion process. The piston acts as a movable end of the combustion chamber transmitting power generated from the burning of fuel and air mixture in the combustion chamber. The objective of this study is to compare the engine performance in horsepower and torque produced by the different shapes of the piston head in an internal combustion engine. Three pistons with different head shapes - standard, mug (low compression) and dome (high compression) with a compression ratio of 8.8:1, 7.61:1 and 10.06:1 were selected for the study. An experiment was also performed to a standard piston installed with 1.5 mm gasket, which has a compression ratio of 7.31. The experiments were carried out using a standard internal combustion engine of a Honda EX5 motorcycle. The engine runs on a chassis dynamometer to measure its torque and horsepower. Piston performance was evaluated based on the maximum available torque and horsepower. The result shows that all three pistons produce different torque and horsepower. The domed piston head produces higher torque and horsepower followed by the standard and mug. By just changing the piston head shape, torque and horsepower increased up to 7.14% and 20.05% respectively.

Keywords: Compression ratio; standard piston; high compression piston; low compression piston.

INTRODUCTION

To comply with emission regulations and increase the power of the engine, technology needs to keep improving. Most research has stated approach in improving engine performance is by changing the compression ratio [1]. Shaik et al. [2] found in his study that compression ratio is one of the parameters that affect thermal efficiency and power. There are varied approached in changing the engine compression ratio, some of them are listed below: -

  i.   Thicker head gasket, which can lower the compression ratio in an engine
  ii. Non-conventional shorter pistons which lower compression in the combustion chamber
  iii. Shorter piston roads and reducing the stroke can lower compression ratio.

iv.   Different shaped piston heads produce different combustion volume.
v.   The use of long duration cams could delay the closing of the intake valve and substantially reduce the compression ratio.

The compression ratio can be adjusted by changing the shape of the piston's head. The clearance volume of the engine is altered by changing the cavity volume of the cylinder head, piston head, and height. This modification facilitates different values of clearance volume [3], which results in different compression ratios.

Good combustion can be influenced by the design of the combustion chambers [4], and the piston head shape plays an important role in the overall design package. Consequently, if different piston head shape can produce more torque and horsepower, it is possible that a smaller engine can be produced. A small engine have lesser weight, therefore, lower fuel consumption. It is conceivable that a piston's shape can influence the exhaust gas, which contributes to air pollution, a global warming issue. There are many aftermarket pistons available, especially for motorcycles. However, the abundance of choice could be confusing for customers when considering the design of piston-head shape and the piston most suitable for daily use. In this regard, this study is focused on the compression ratio effect from different shapes of the piston head, on torque and engine horsepower. This study can help users in selecting the right piston.

Piston Head Shape

Piston head shape has a significant effect on the internal combustion process. Mainly, the shape of a piston head determines how heat and the air/fuel mixture are managed. A piston head is a part of the combustion chamber, and the change in the piston head shape changes the shape of the combustion chamber area. In designing an engine, combustion chamber shape should be closely considered, as it is one of the parameters that influence engine performance [5] . In this light, Saito et al. [6] investigated the effects of combustion chamber geometry and found that engine performance changes if the combustion chamber design is altered.

Numerous research have been done on the shape of the piston head. Bawankar et al. [7] in his study on four different piston heads (hemispherical, omega, single curved and double curved) found that different piston head shapes produce different engine performances. The grooved head piston increases the swirl and the turbulence, which improves fuel-air mixing [8] and brake thermal efficiency [9]. Prasanti et al. [10] studied the influence of the air swirl in the cylinder on the performance and emission. The intensification of the swirl was conducted by cutting grooves on the crown of the piston. In this study 6, 9 and 12 grooves used to intensify the swirl for better mixing of fuel and air. From the investigation, piston with 9 grooves gives better performance in all aspects, such as thermal brake efficiency and brake specific fuel consumption.

Gasoline and air mix together in the combustion chamber above a piston. Pistons that are elliptical, or shaped like ovals, become more circular when the heat is applied. This improves sealing gaps when the cylinder meets the combustion chamber resulting in greater efficiency. Some pistons are tapered or conical, which lets the piston move more freely regardless of how much heat is present. Others are "barrel" shaped, which is smoother and generates less noise and harshness as it moves [11] . Channappagoudra et al. [12] in his other study revealed that the modified engine with Re-entrant Toroidal Piston Bowl Geometry (RTPBG) showed improved performance, combustion and emission characteristics when compared with different piston bowl geometries, namely Hemispherical Piston Bowl Geometry (HPBG), Straight Sided Piston Bowl Geometry

(SSPBG) and Toroidal Piston Bowl Geometry (TPBG). This improvement could be attributed to improved fuel atomisation, smaller size droplets, increased cylinder temperature, swirl and squish, the turbulent kinetic energy of the charge during combustion.

Compression Ratio

In an internal combustion engine, a piston compresses a large volume of a mixture comprised of fuel and air into a very small space. The ratio of the maximum piston volume to the minimum compressed volume is called the compression ratio. Varying compression ratios offer a diverse potential of combustion efficiency, which can be translated to torque and horsepower under varying loads and speed conditions [13, 14]. The compression ratio is defined as the difference between the volume in the combustion chamber above the piston when the piston is at the bottom dead centre (BDC) to the piston at the top dead centre (TDC) [15]. The Pressure-Volume diagram in Figure 1 shows the relationship between pressure and volume in a combustion engine. The area of the cycle 12341 or area ABCDA represents the indicated work (W_i) done in a cycle. Based on Eq. (1) and (4), the higher compression ratio produces higher work, translated as engine performance [5, 16].

A larger piston height takes up some of the available volumes in the combustion chamber compared to a smaller piston height, thus changing the compression ratio of the engine as given in Eq. (1). Abhishek Reddy et al. [17] study concluded that higher compression ratio produces higher brake thermal efficiency and higher brake power. This could also be proven by the Eq. (1), (2) and (3), which indicates that the higher compression ratio increases thermal efficiency. Referring to Eq. (1) and (2), when the piston height is changed, brake thermal efficiency, η_T of an engine changes. On the other hand, for the same tyfpe of fuel or the same value of Q_{in}, Eq. (3) shows that thermal brake efficiency, η_T increases when the brake power increases. For this experiment, theoretically, the thermal efficiency can be calculated based on the Eq. (1) and (2). For the given specific heat ratio, γ of 1.3 and the calculated compression ratio, r_c, the standard piston has a thermal efficiency of 48%, while high compression and low compression piston have 50% and 46% respectively. For a piston that has 1.5 mm gasket installed, it has 44% thermal efficiency. \

$$r_c = \frac{V_D}{V_A} = \frac{Volume\ at\ BDC}{Volume\ at\ TDC} \tag{1}$$

$$\eta_T = \left(1 - \frac{1}{r_c^{\gamma-1}}\right) \tag{2}$$

$$\eta_T = \frac{B_p}{Q_{in}} \tag{3}$$

$$mep = \frac{w}{V_D - V_A} \tag{4}$$

where η_T is thermal efficiency, r_c is compression ratio, γ is specific heat ratio of ~1.3-1.4, B_p is brake power, Q_{in} is heat by fuel, *mep* is mean effective pressure and; w is work.

There are many ways to change the compression ratio in the combustion chamber. Gupta et al. [18] in his experiment changed the compression ratio of the engine by moving the cylinder head and the liner assembly of the piston up and down. The compression ratio

can also be changed by milling the top head piston or adding a thicker head gasket [19]. Other than that, using a piston with a different piston head design or a cylinder head with a different chamber size can also change its compression ratio. It is the sizes of the piston head and chamber that affect the ratio between the volume at BDC and TDC within the combustion chamber. Attard et al. [20] increased the compression ratio from 9 to 13 by changing the shape of the piston head experimentally and found that BSFC improved as compression ratio increased. The compression ratio can also be improved by changing the stroke-to-bore ratio. Long stroke engines produce high compression ratio, which results in better BSFC and overall engine performance [21].

Fu et al. [22] in his experiment found that the torque and thermal efficiency of LME (liquefied Methane Engine) could be improved by increasing the compression ratio. Under the operating conditions, the torque of LME could be increased by 9.5%. Yuh et al. [23] investigated the effect of a higher compression ratio on power output for an air-cooled two-stroke motorcycle engine. The results show that actual fuel consumption improves by 1-3% for each increasing unit of compression ratio over the ratio range of 6.6 to 13.6. However, they found that higher compression ratio could cause serious problems such as knock and piston thermal load increase. Furthermore, Aina et al. [24] found that brake power increases as the compression ratio increases.

EXPERIMENTAL SETUP

Engine Specification

In this experiment, a standard Honda EX5 motorcycle engine was used. It is a naturally aspirated four stroke small air cooled engine with 8.1 Nm torque at 6000 rpm. The standard compression ratio, as well as other engine specifications, are shown in Table 1. Before the test was conducted, the engine was overhauled, and some damaged parts were replaced. The lubricant oil was changed along with the damaged gasket found during each piston replacement. Parameters such as room temperature, room air pressure, and humidity were measured before and during experiment.
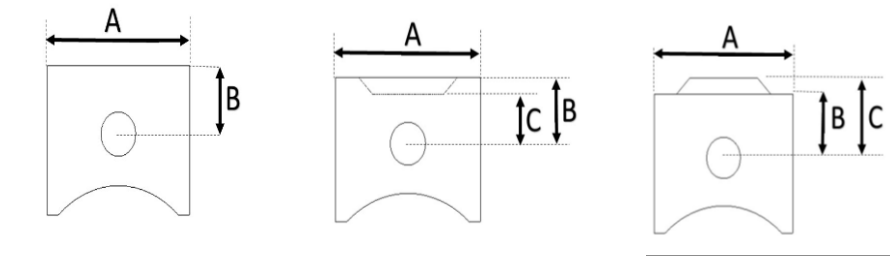
Table 1. Engine specification.

Parameters	Value
Make model	Honda C100 EX Super Cub (EX5 Dream)
Engine	Single Cylinder, 4 Stroke, OHC
Capacity	97 cc / 5.9 cu in
Bore × stroke	50 × 49.5 mm
Cooling system	Air cooled
Compression ratio	8.8:1
Ignition	CDI
Max power	5.9 kW / 8.0 hp @ 8000 rpm
Max torque	8.1 Nm @ 6000 rpm
Transmission	4-speed continuous

In this experiment, the compression ratio was changed by using three different types of piston, as shown in Table 2. The differentiating features of the three pistons were the head shape. The low compression piston has a mug head shape whereas a high compression piston has a dome head shape. All pistons are made of the same material,

with a diameter of 53 mm and a length of 19.55 mm between piston pin and piston head. The difference is the length, C, which is 13.55 mm for low compression piston and 26.75 mm for high compression piston respectively.

Table 2. Piston type.

Piston type and dimension	Standard	Low compression (mug type)	High compression (dome type)
C	0 mm	13.15 mm	26.75 mm
A	53.00 mm	53.00 mm	53.00 mm
B	19.95 mm	19.95 mm	19.95 mm

During the experiment, the motorcycle was placed on a chassis dynamometer. It is a single roller with an eddy brake dynamometer type. The rear tire was placed on the dyno drum. For safety purposes, the motorcycle was secured to the dynamometer. There are two variations of the experiment which can be used using a chassis dynamometer, a steady state test where the engine runs under a selected load and speed or zero to maximum test where the maximum speed is achieved (wide open throttle) [25]. In this experiment, zero to maximum test was performed where the engine was tested under no load. The data (torque and horsepower) was taken for the 3rd and 4th gear where it was recorded from 3000 rpm until the throttle was fully open and the engine achieved the maximum rpm. Four experiments were conducted in this study as listed:-
    i.   Torque and horsepower on the standard piston
    ii.   Torque and horsepower on the standard piston with additional 1.5mm gasket
    iii.   Torque and horsepower test on the low compression piston
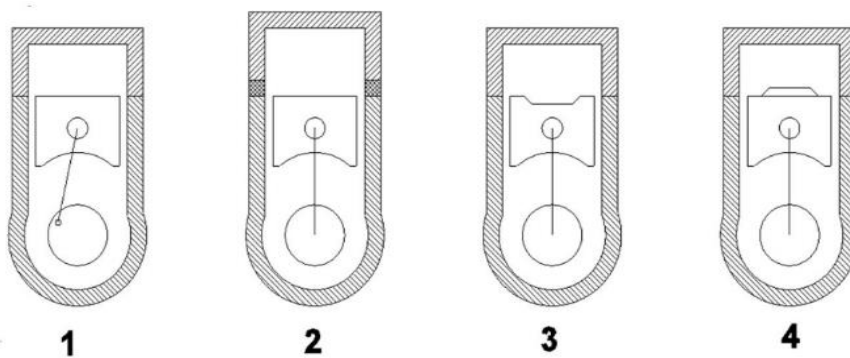   iv.   Torque and horsepower test on the high compression piston.
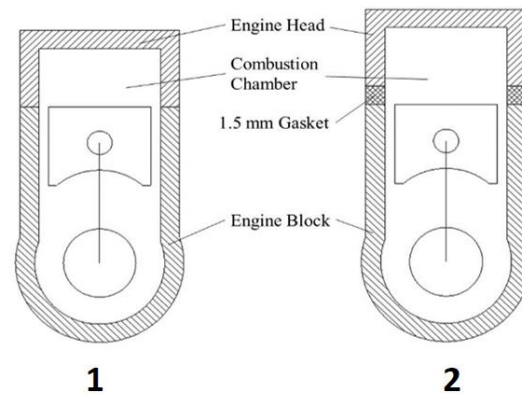
Figure 2. Experiment configuration.

Figure 3. Engine diagram with and without a gasket.

Figure 2 shows the configuration for all four experiments. Theoretically, due to different piston head shapes, each experiment has a different compression ratio. Referring to Figure 2, test 1 has a compression ratio of 8.8:1, test 2, 3, and 4 have a compression ratio of 7.31:1, 7.61:1 and 10.6:1 respectively.

As shown in Figure 3, a similar type of piston used in the first and second experiment. However, for the second experiment, 1.5 mm gasket was added to the engine head. As a result, the volume in the combustion chamber was increased, which reduced the compression ratio. This allows a direct comparison of the compression ratio using the same head shape as the standard piston.

On the other hand, different types of piston head were used (low and high compression piston) in the third and fourth experiments. Consequently, the changes in the piston head shape changed the volume in the combustion chamber. The use of the high compression piston reduced the combustion chamber volume, which increased the compression ratio. While the use of high compression piston reduced the volume, the use of the low compression piston increased the volume in combustion, and this reduced the compression ratio in the combustion chamber. The resulting observation motivated the addition of a 1.5 mm gasket to the engine head to reduce the compression ratio.

RESULT AND DISCUSSION

Power and Torque for Standard Piston

Figure 4 shows a comparison of the power produced by two different engine settings: with and without a 1.5 mm gasket. The power produced from both experiments gradually increased from the beginning until the end of the experiment. Both experiments showed the same pattern. However, from the overall result, a standard piston without gasket had the higher power than that with a 1.5 mm gasket. At 3000 rpm, standard piston without gasket produces 2.99 bhp power and that with a 1.5 mm gasket has 2.9 bhp or 3% less power. The highest power produced by the engine without a gasket is 8.42 bhp at 8324 rpm and the engine with a 1.5mm gasket, at the same rpm, produced 8.19 % less power at 7.73 bhp.
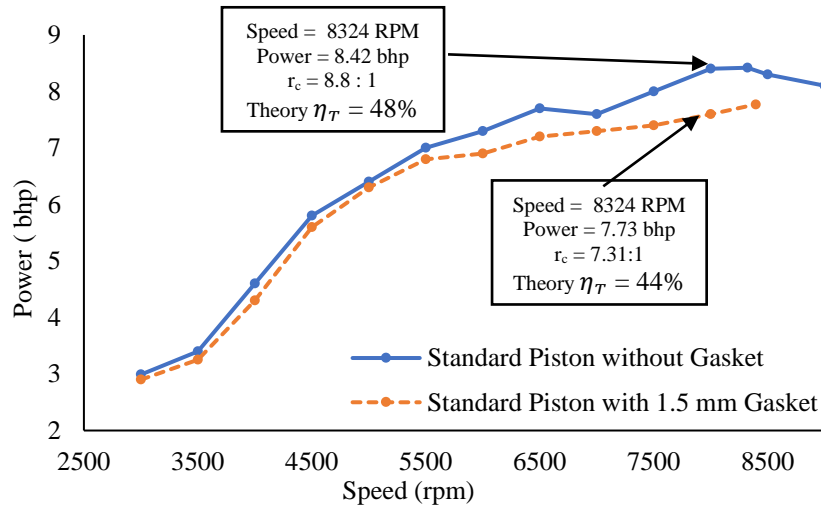
Figure 4. Power comparison for the a standard piston with and without gasket.

As shown in Figure 5, both engine settings have a similar torque curve pattern. The torque for both settings increases when the rpm is raised and reached its maximum at 4500-5500 rpm. However, at a higher rpm, the torque decreases to its previous value. At 3000 rpm, the engine without the gasket has the torque of 7.1 Nm, and that with 1.5 mm gasket has 6.9 Nm or 2.8% lower torque. The highest torque for the engine without a gasket is 9.4 Nm at 5099 rpm, and for the engine with 1.5 mm gasket, at same rpm, its maximum torque is 8.96 Nm or 4.68% lower.
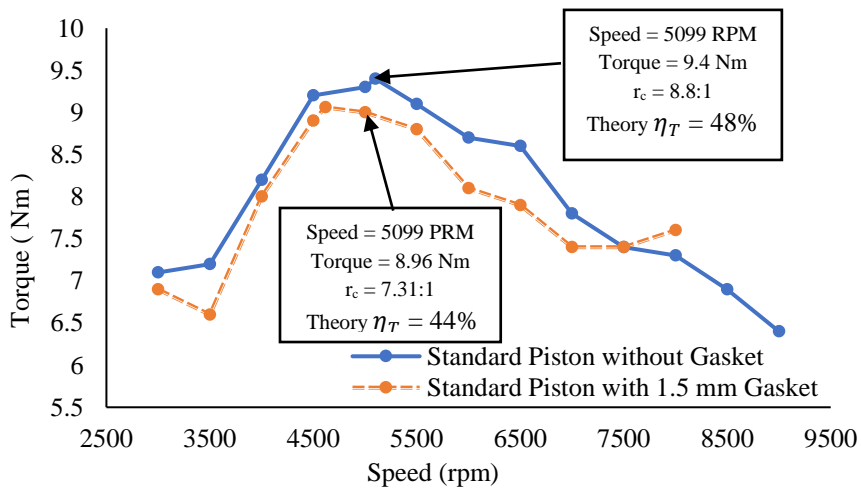
Figure 5. Torque comparison for the standard piston with and without gasket.

Both resulting torque and horsepower show that high compression ratio produces high torque and horsepower. El-Adawy et al. [26] also found that the higher the compression ratio of the engine, the higher the torque obtained from the engine. Theoretically, a standard piston has a thermal efficiency of 48% and a piston with a 1.5 mm gasket has 44%. The results show that an engine with a thermal efficiency of 48% produced higher torque and power compared to an engine having a thermal efficiency of 44%. The result is similar to the experiment done by Abhishek Reddy et al. [17] and Fu al. [22]. Bridjesh et al. [27] also found that by lowering compression ratios from 17.5:1 to

13.7:1 in two steps by using thicker head gaskets, brake thermal efficiency of the engine drops. Lower brake thermal efficiency means lower brake power.

Power and Torque for Low and High Compression Piston

The third and fourth experiments were conducted to compare the torque and horsepower between low and high compression pistons. Figure 6 shows the result of the power produced by both pistons. Both curves have a similar pattern, but the overall result showed that a high compression piston produces higher power than a low compression piston. At the initial stage, the high compression piston produced 3 bhp, and the low compression piston produced 2.2 bhp, which is 26.6% lower power. The highest power produced by the high compression piston is 9.28 at 8680 RPM while the low compression piston produced 10.45 % less power at 8.31.

Concerning the torque as in Figure 7, both curves showed a similar pattern that started at a lower torque before reaching their maximum and decreasing as the speed increases. The maximum torque produced at 5089 rpm for high compression piston was 9.6 Nm while for the low compression piston was 8.98 Nm. The results are similar to what is reported in previous research where high compression produced high power [17, 22-24]. The result also shows that the high thermal efficiency piston of 50% has higher torque and horsepower compared to lower thermal efficiency piston at 46%. It is similar to the findings from a previous study by Channappagoudra et al. [9] and Bharathi et al. [10]. Both researchers claimed that different head piston shape help in producing a swirl effect which increases thermal efficiency
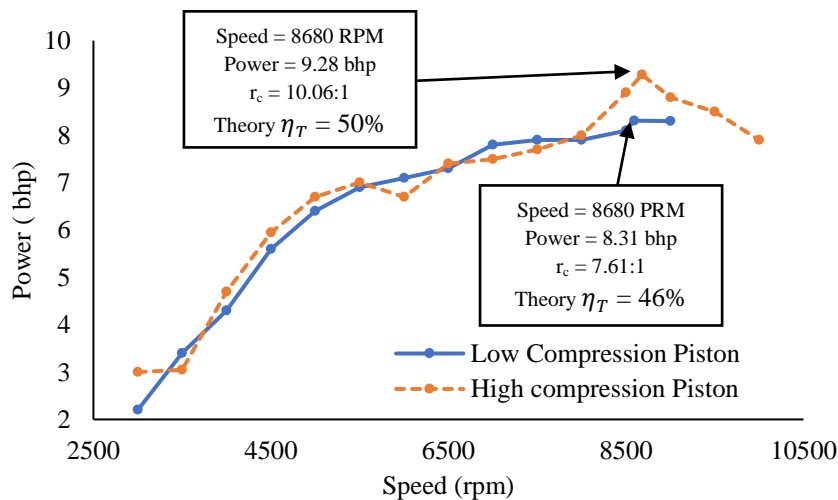

Figure 6. Power comparison between low and high compression piston.

Figure 6 and Figure 7 also show a line intersection between low and high compression piston after reaching its highest torque and power. It is true that if pressure is too high, it can affect the engine performance. Yuh et al. [23] found that higher compression ratio could cause serious problems such as knock and piston thermal load increase. Knocking can come from pre-ignition during combustion. There are many causes of pre-ignition and one of them is the type of fuel used in the experiment. Binjuwair et al. [14] found that in comparing between RON 95 and RON 91, RON 91 showed better performance by 0.54 % at a compression ratio of 10.5:1. In this experiment, only fuel type

RON 95 was used. Yuh et al. [23] also found in the experiment, as the compression ratio raised from 6.6 to 13.6, mechanical loss increases by 27 %. It could come from the friction produced during high speed. As the engine is raised above the speed, its torque starts to decrease due to the increased friction of the engine's moving parts. This could reduce torque and power produced at high speed.
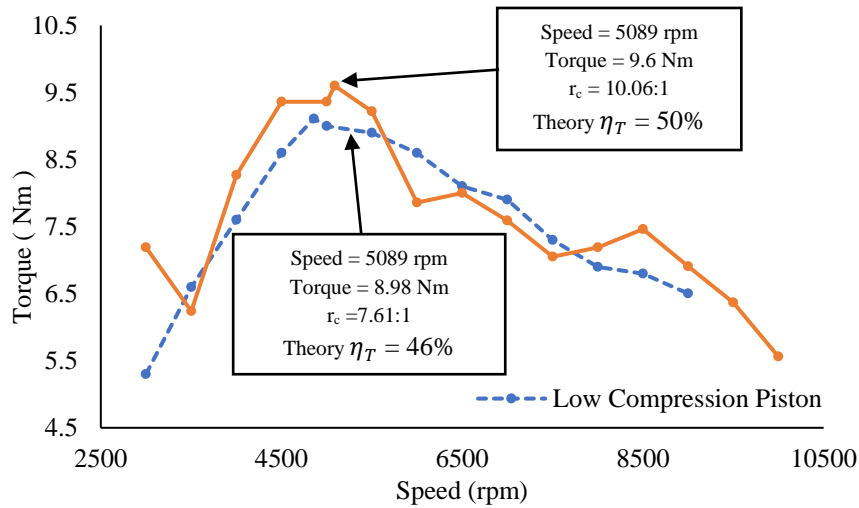

Figure 7. Torque comparison between low and high compression piston.

Figure 8 shows a comparison between the highest torque and power produced in all of the experiments. It shows that high compression piston produces the highest power at 9.28 bhp followed by the standard piston at 8.42 bhp. Meanwhile, the low compression piston and the standard piston with 1.5 mm gasket recorded 8.31 bhp and 7.73 bhp respectively. Same as power, the high compression piston produced the highest torque at 9.6 Nm, followed by the standard piston, low compression piston and the standard piston with 1.5 mm gasket at 9.4 Nm, 8.98 Nm and 8.96 Nm respectively.
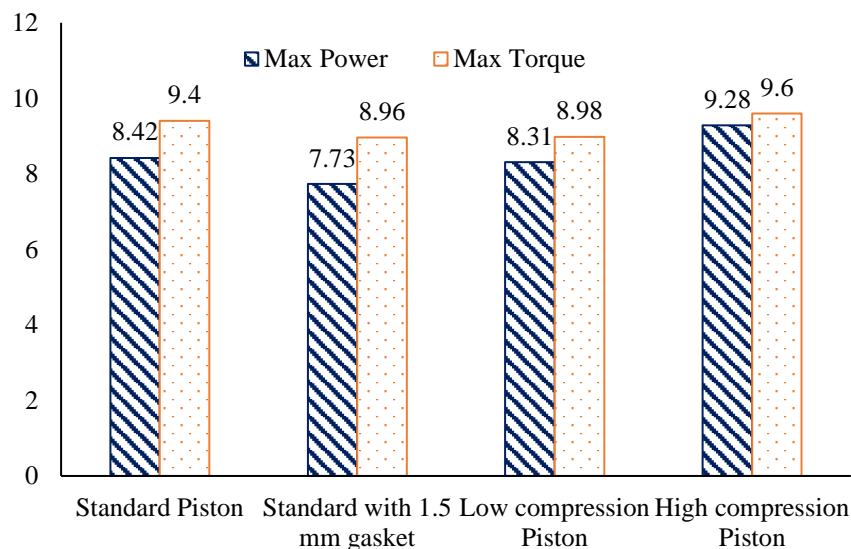

Figure 8. Comparison of the highest power and torque.

The result showed that the high compression piston increased its torque and horsepower by 2.12% and 10.21%. On the other hand, the low compression piston decreased its torque and horsepower by 4.46% and 1.3%. The engine with a 1.5 mm gasket produced lower torque and horsepower by 4.68% and 8.19% respectively. From Figure 8 below, the difference between the highest and lowest torque for all 4 experiments is 7.14%, and for power, it is about 20.05%. Chunkaew et al. [28] in his experiment reported similar observations that the brake power of the compression ratio of 9.3:1 is higher than the compression ratio of   7.5: 1.

In term of thermal efficiency, a high thermal efficiency engine produces higher torque and horsepower. A high compression piston that has 50% thermal efficiency produced 9.6 Nm of torque and 9.28 bhp of brake horsepower compared to a standard piston with 48% thermal efficiency producing less torque and horsepower at 9.4 Nm and 8.42 bhp respectively. The results are supported by the equation, $\eta_T = \dfrac{B_p}{Q_{in}}$, which shows at the same Q_{in} (same quality of fuel), higher thermal efficiency, η_T produced higher brake power B_p. The results are similar to the basic theory of an ideal Otto cycle and from Eq. (1), (2) and (3). The increasing compression ratio is the most significant approach to increasing the thermal efficiency which relates to the increased torque and power of engine [9] [10] [17] [22] [27].

CONCLUSION

The compression ratio is the ratio between the volume at the bottom dead centre to the volume at top dead centre. Even though the power and torque produced in this experiment are uneven, the high compression piston produces the highest torque and power. This can be represented by the compression ratio formula, $r_c = \dfrac{V_D}{V_A} = \dfrac{Volume\ at\ BDC}{Volume\ at\ TDC}$, which influences the torque and horsepower of the engine. The overall result found that the highest compression ratio of 10.06: 1 produced highest torque and horsepower at 9.6 Nm and 9.28 bph respectively while lowest compression ratio of 7.31:1 produced only 8.96 Nm and 7.73 bhp which shows that the maximum compression ratio corresponds to maximum brake power and torque. The result also shows that by just changing the piston head, the torque and power can be improved up to 7.14% and 20.05% respectively. It also shows that engine performance can be increased by changing the piston head shape without the need for complex modification. It means that higher torque and horsepower can be produced from a similar sized engine. Smaller sized engines with similar or higher performance can also be produced. In this regard, a smaller sized engine translates to less weight and lower fuel consumption. For future studies, several experiments can be done, such as studying the air flow in the combustion chamber, the temperature of the engine, gas emission, and fuel consumption.

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