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Performance and Emission Analysis of Piston Bowl Type and Depth Variations on Diesel Engine Shark R180

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ABSTRACT

The performance and emission study on the different types of piston bowls and the depth variation of the piston bowl is discussed in this paper. Simulations were conducted using the open-source software, Diesel-RK. Three models of piston bowls and five variations of piston depth were used to estimate performance and emissions. The type of fuel and engine operating conditions were set to be constant. The performance responses consist of power, Specific Fuel Consumption (SFC), and brake mean effective pressure (BMEP). On the other hand, the emissions of NOx and Particulate matter (PM) were analyzed. Results show that both power response and BMEP improve with an increase in piston depth across all types of piston bowls. On the contrary, the SFC trend line shows a decline as piston depth increases. For the emissions, NOx experiences a rising trend as the depth of the piston bowl increases at all types of piston bowls. Conversely, the particulate matter (PM) trend is decreasing as the depth of the piston bowl increases.

KEYWORDS: *Diesel engine, Piston bow, Piston depth, Performance, Emission.*

NOMENCLATURE

$BMEP$	Brake Mean Effective Pressure
SFC	Specific Fuel Consumption
$SFOC$	Specific Fuel Oil Consumption
NO_X	Nitrogen Oxides
PM	Particular
RPM	Pressure Force

1. INTRODUCTION

With their large capacity and high efficiency, ocean-going vessels are the main means of distributing goods across countries and continents. Diesel engines are chosen for marine vessels due to their efficiency, power, and low fuel consumptions [1]. Because of its advantages, diesel engines are widely utilized in the maritime sector, despite producing high emissions [2]. The main pollutants produced by diesel engines are NOx and PM [3]. Diesel engines are the main contributors to PM and NOx emissions [4]. NOx and PM are the most dangerous pollutants [5]. The ship can produce NOx of 7 billion tonnes per year and PM of 1.6 billion tons per year [6]. Particulate matter (PM) can cause various health impacts, such as premature death in individuals with a history of heart or lung disease, non-fatal heart attacks, heart rhythm disturbances, and reduced lung function performance [7]. Emissions of NOx from diesel engines contribute to environmental issues like air pollution, smog, and acid rain, and have harmful effects on respiratory health, potentially leading to illnesses such as bronchitis, bronchiolitis, and pneumonitis. [8]. Research and innovation are needed to minimize NOx and PM emissions [5]. Various regulations, such as MARPOL Annex VI and Euro standards, are implemented to reduce emissions, including the use of emission control technology. In Indonesia, Euro 4 has been in effect since 2021, and Euro 5 is planned for 2025 to reduce air pollution.

The high health risks of air pollution have prompted studies to find ways to minimize emissions from diesel engines [9]. The emissions generated by diesel engines are affected by multiple factors, such as the air-fuel ratio, compression ratio, preheating of air and fuel, composition of the fuel mixture, design of the combustion chamber, timing and pressure of fuel injection, and the application of exhaust gas recirculation [10]. Although diesel engines are often chosen because of their capabilities, they still have some problems that cause the performance of diesel engines to be less than optimal [11]. To get the maximum performance from a diesel engine, several aspects need to be considered. Among them are air fuel ratio, Injection Timing, and ambient, or the amount of energy produced from fuel combustion depends on the amount of oxygen contained in the surrounding dry air [12]. One way is to

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change the variation of the piston bowl shape. The shape of the piston bowl plays an important role in mixing air and fuel in the combustion chamber [9]. Combustion chamber design is a very important part of the overall engine system to achieve standardized combustion and improve engine efficiency [13].

Research by Habtamu Deresso et al. compared four piston bowl models to reduce NOx and PM emissions. The study revealed that the highest peak cylinder pressure occurs in Shallow Hesselman (131 bar) and the lowest in DOOSANP158FE (113 bar), with a difference of 13.8%. The maximum cylinder temperature was also highest in Shallow Hesselman (2048 K) and lowest in DOOSANP158FE (1681 K), with a difference of 18%. PM emissions were lowest in DOOSANP158FE (0.24 g/kWh) and highest in Piston-3 (0.43 g/kWh), while NOx emissions were highest in Piston-1 (25.62 g/kWh) and lowest in Piston-4 (12.74 g/kWh). This study did not assess the performance of the diesel engine used [9].

Research by Iswantoro et al compared a standard piston and a modified piston with an additional depth of 1 mm.As a result, the standard piston exhibits superior performance, although the difference is not very large. The lowest torque of 5.917 Nm and the lowest SFOC of 267.185 g/kWh occurred on a standard piston bowl at 1900 RPM. The highest SFOC, 624.959 g/kWh occurred on a modified piston bowl at 2100 RPM. The highest power of 5.436 kW was owned by standard piston 4 at 1900 RPM, and the lowest power of 1.178 kW by standard piston 1 at 2100 RPM. This study only varied the depth on one type of piston bowl [14].

Research by Van Chien Pham et al compared three piston bowl to see their effects on combustion and emissions. The results showed that the ω type and Re-entrant type increased cylinder power by 1.26% and 2.67%, and decreased SFC by 1.06% and 1.60%, and reduced NO emissions by 25.61% and 46.09% respectively, compared to U type. The study only discussed variations in piston bowl shape with one size for each type [2].

Two objectives are addressed in this study. First, analysis of the performance and emission resulting from the variation of piston bowl (such as U type, ω type, and Re-entrant type) is observed. Second, the effect of piston bowl depth is also considered in this current research. The simulation is running using Diesel-RK software with a model of the diesel engine of Shark R-180.

2. METHODS

Simulations are conducted using Diesel-RK software to estimate the performance of the diesel engine and the amount of NOx and PM emissions from marine diesel engines. Diesel-RK is an innovative software developed by Bauman Moscow State Technical University in Russia, with the primary goal of enhancing the efficiency of the combustion process in diesel engines [9]. More precisely, this software is intended to simulate and optimize the working process of internal combustion engines with all types of thrusters [15]. Therefore, Diesel-RK is very suitable for young researchers because its multifunctional open-source software.

For completeness, a simplified sketch of Shark Diesel Engine type R-180 and its specification that used for simulation data in this study is added, as mentioned in figure 1. A Shark R-180 engine is a new research apparatus facility from Universitas Pembangunan Nasional "Veteran" Jakarta to conduct the experiment in marine diesel engine field. Shark engine is a four-stroke diesel engine with an inline single-cylinder configuration. This engine is capable of producing an average power of 5.15 kW or 7.2 PS at 2600 RPM. Its bore and stroke dimensions are 80 mm each. This engine has a compression ratio of 22:1.

Engine Specification	
Model	Shark R180
Engine Type	(4-Stroke, Inline, Diesel Engine)
Number of Cylinder	1
Bore x Stroke [mm]	80 x 80
Compression Ratio	22
Rated Output [kW]	5.15
RPM	2600

Figure 1: Shark R180 engine specification

Figure 2 shows the variation of the piston bowl type that was used in this simulation, such as U type, ω type, and Re-entrant type. As illustrated in the same figure, the vertical axis represents the depth of the piston bowl, which is varied to estimate the amount of NOx, PM, Power, SFC, and BMEP in a marine diesel engine. In more detail, the piston bowl depth refers to the maximum distance from the piston's top surface to the lowest point of the bowl. This measurement represents the depth of the combustion chamber within the piston [16].

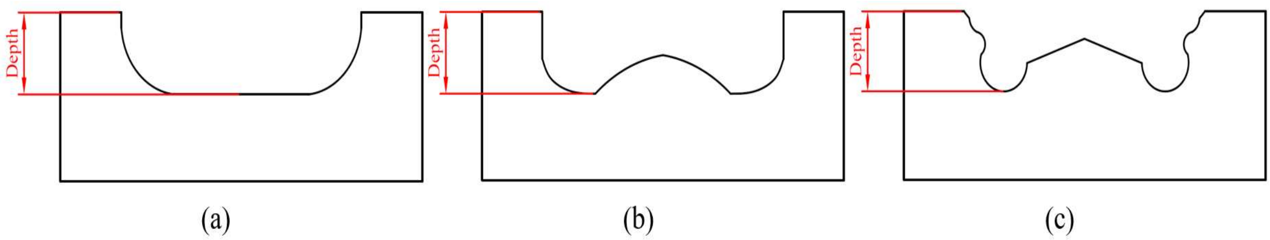

Figure 2: The piston bowl variation that used in this current study (a) U Type Piston Bowl, (b) ω Type Piston Bowl, (c) Re-Entrant Type Piston Bowl

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Table 1 presents the variation of depth of the piston bowl shape under different of three different types of piston bowl that are used in this current study. The outputs of both variations are same: the emissions of NOx, PM, Power, SFC, and BMEP. The original depth of the piston bowl of the Shark R-180 engine is called "standard" in this current paper. Then, the depth varies in the positive direction of +1, +2, and the negative direction of -1, -2. So, there are a total of 5 different conditions of depth. It can be noted that the display value is a scale proportional to the piston bowl Shark R-180 depth. The scale on the piston bowl is determined by matching the size of the engine bore. The engine bore from the reference journal is scaled so that its bore size is the same as that of the Shark R180 engine. By matching the size, the shape of the piston bowl from the reference journal does not change significantly.

Table 1: Simulation condition under different depth

Depth (mm)	Piston Bowl Type			Output
	U Type	ω Type	Re-entrant Type	
-2	12.545	12.590	12.250	Power, SFC, BMEP, NOx, and PM
-1	13.545	13.590	13.250	
Standard	14.545	14.590	14.250	
+1	15.545	15.590	15.250	
+2	16.545	16.590	16.250	

All simulations conducted in this performance and emissions study only focused on variations in the shape and depth of the piston bowl. Other variables probably have an impact on the emissions, such as the type of fuel and engine operating conditions. Therefore, those variables were kept constant so as not to influence the analysis results. In this case, our study uses diesel fuel as a fuel and engine speeds of 2600 rpm. In addition, it is meaningful in the present study to ensure that differences in engine emission and performance were entirely due to differences in piston bowl shape.

Before a run, the validation process is a mandatory procedure to make sure our model is correct or not. Two types of validation methods are applied in the present study. First, the comparison of the gap between our data from the Diesel-RK simulation to the engine specification of the Shark R-180 is used. The output power in kW and specific fuel oil consumption (SFOC) in g/kWh are considered. The results show that the gap of power output is quite low, at 1%. On the other hand, the gap of the SFOC is around 5%. Please note that this result graph is not present in this current paper.

Second, Validation is carried out by comparing the simulation results obtained through Diesel-RK software against data taken from reference journals, where this comparison is based on U type piston bowl shape. In the comparison process, the parameter of cylinder pressure is used. Again, validation was conducted to compare the simulation results from Diesel-RK with the research results by Mohamed Khaled Abdelrazek [10], as shown in Figure 3. The horizontal and vertical axes are crank angle in degree units and cylinder pressure in bar units. As we can see, in the beginning crank angle of 300 and at the end of 380, the values of cylinder pressure are quite similar. In contrast, at 320 - 360 crank angle, experiencing a slight increment gap. It is probably due to the difference in the injection timing. Retarding the injection timing will decrease the ignition delay, peak temperature in the cylinder, and maximum heat release rate [17].

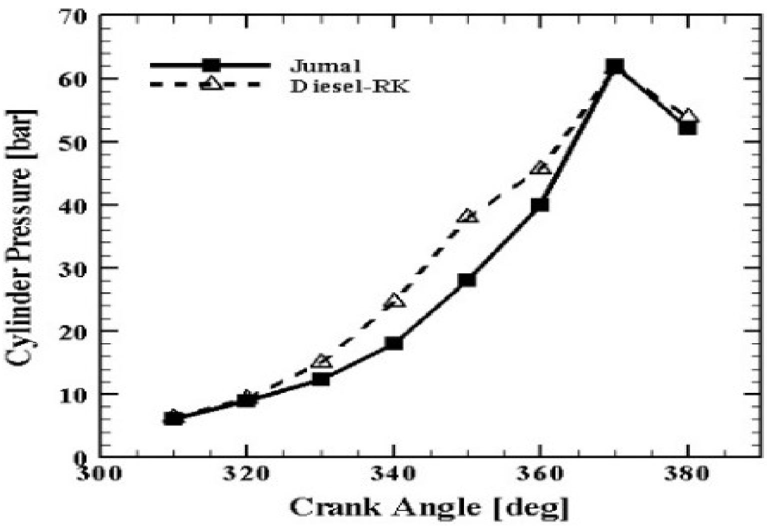

Figure 3: The validation between Mohamed Khaled Abdelrazek [10] and the current study

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3. RESULTS AND DISCUSSIONS

Figure 4 is a comparison chart between variations in piston bowl depth and engine power. U Type shown an upward trend in power as the depth of the piston bowl increases. The power generated is 5.2707 kW at a depth of -2, 5.2743 kW at -1, 5.2756 kW at standard depth, 5.2788 kW at +1, and reaches a maximum value of 5.2816 kW at a depth of +2. ω type also shows a similar trend, from 5.2702 kW at a depth of -2, 5.2718 kW at -1, 5.2720 kW at standard depth, 5.2752 kW at +1, and reaches a maximum value of 5.2776 kW at a depth of +2. Re-entrant type also shows a similar trend to other types, starting from 5.2629 kW at a depth of -2, 5.2644 kW at -1, 5.2655 kW at standard depth, 5.2694 kW at +1, and reaches a maximum value of 5.2747 kW at a depth of +2. Overall, all piston types showed an increase in power as the bowl depth increased, with U type being the highest and Re-entrant type being the lowest.

Modifications in the depth of the piston bowl can also impact the engine's power output. Increasing the piston bowl depth makes the combustion chamber volume also increase, which provides more space for the airflow to move and increase swirl intensity. This stronger swirl leads to more effective atomization and evaporation of fuel, resulting in better mixing of air and fuel and more efficient combustion [18]. As a result of efficient combustion, the engine produces more power [19].

Figure 5 is a comparison chart between variations in piston bowl depth and specific fuel consumption (SFC). For U Type, specific fuel consumption decreases as the depth of the piston bowl increases, starting from 0.25985 kg/kWh at depth -2, 0.25969 kg/kWh at depth -1, 0.25963 kg/kWh at standard depth, 0.25947 kg/kWh at depth +1, and reaching a minimum value of 0.25933 kg/kWh at depth +2. ω type shows a similar downward trend, from 0.25990 kg/kWh at depth -2, 0.25983 kg/kWh at depth -1, 0.25982 kg/kWh at standard depth, 0.25966 kg/kWh at depth +1, and reaching a minimum value of 0.25954 kg/kWh at depth +2. Re-entrant type also shows a similar trend to other types, starting from 0.26028 kg/kWh at depth -2, 0.26021 kg/kWh at depth -1, 0.26015 kg/kWh at standard depth, 0.25996 kg/kWh at depth +1, and reaching a minimum value of 0.25969 kg/kWh at depth +2. Overall, all three piston types show a decrease in specific fuel consumption as piston bowl depth increases. The Re-entrant type has the highest fuel consumption, while the U Type is the most fuel-efficient.

In relation to the previous discussion, high intensity swirl resulting from the increased combustion chamber volume helps improve the efficiency of fuel droplet atomization and evaporation [18]. This leads to better combustion and helps the fuel burn better [20]. The reason is that the time required for the fuel to reach its flash point becomes shorter due to the higher temperature produced [21]. It helps to improve combustion efficiency [20]. It also helps the engine to produce more power with reduced fuel consumption [19]. As engine power increases, the SFC value decreases, indicating more efficient fuel consumption [14].

Figure 6 is a comparison graph between variations in piston bowl depth against brake mean effective pressure. For U type, Brake Mean Effective Pressure (BMEP) increases as the depth of the piston bowl increases, starting from 6.0494 bar at depth -2, 6.0536 bar at depth -1, 6.0551 bar at standard depth, 6.0588 bar at depth +1, and reaching a maximum value of 6.0620 bar at depth +2. ω type also shows a similar trend, starting from 6.0489 bar at depth -2, 6.0507 bar at depth -1, 6.0509 bar at standard depth, 6.0546 bar at depth +1, and reaching a maximum value of 6.0574 bar at depth +2. Re-entrant type also shows a similar trend to other types, starting from 6.0405 bar at depth -2, 6.0422 bar at depth -1, 6.0435 bar at standard depth, 6.0479 bar at depth +1, and reaching a peak value of 6.0541 bar at depth +2. Overall, all types show an upwards trend in BMEP as the depth of the piston bowl increases. The re-entrant type has the lowest BMEP, while the U type produces the highest BMEP.

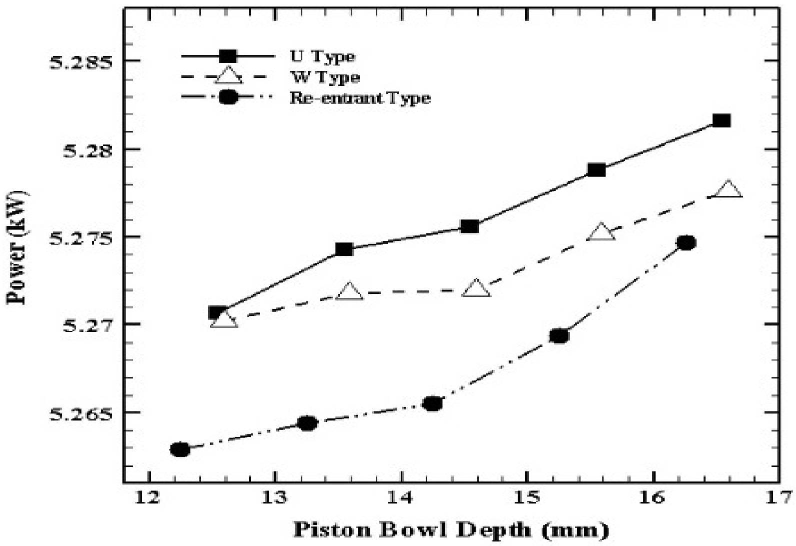

Figure 4: Comparison of power for U type, ω type, and Re-entrant type at different bowl depths

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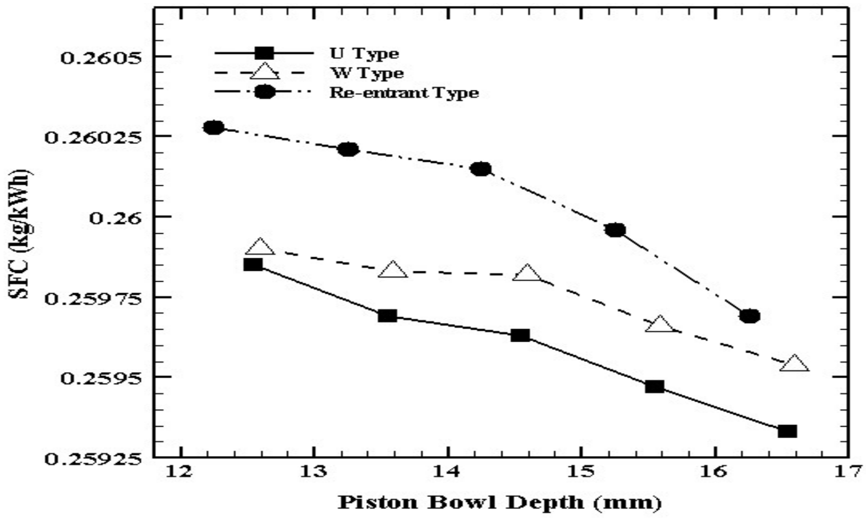

Figure 5: Comparison of SFC for U type, ω type, and Re-entrant type at different bowl depths

As mentioned in the previous discussion, increasing the piston bowl depth increases the combustion chamber volume, providing more space for airflow and enhancing swirl intensity. This stronger swirl improves fuel evaporation, leading to a more homogeneous air–fuel mixture. As a result, combustion becomes more efficient, and cylinder temperature increases [18]. As fuel vaporization gradually improves, more energy is transformed into engine power. At the same time, this process also raises the cylinder temperature, which contributes to a rise in BMEP. BMEP increases as cylinder temperature increases [22]. BMEP has a direct relationship with engine power [23]. Higher BMEP leads to higher engine power and more effective fuel use [22].

Figure 7 displays a comparison chart between piston bowl type (U type, ω type, and Re-entrant type) against NOx emissions at each piston bowl depth variation -2, -1, Standard, +1, and +2. U type produces the lowest NOx emissions at depth variation -2 with 1376 ppm and the highest NOx emissions at depth variation +2 with 1410.2 ppm. ω type produces the lowest NOx emissions at depth variation -2 with 1375.4 ppm and the highest NOx emissions at depth variation +2 with 1401.9 ppm. The Re-entrant type produced the lowest NOx emissions at depth variation -2 with 1331.5 ppm and the highest NOx emissions at depth variation +2 with 1372.7 ppm. As we can see in this graph, several facts can be taken. First, the Re-entrant type is the type that produces the lowest NOx emissions across all piston bowl depth variations in ppm units. Contrarily, the U type becomes the highest producer of NOx in every depth of the piston bowl. In addition, ω type is the middle one.

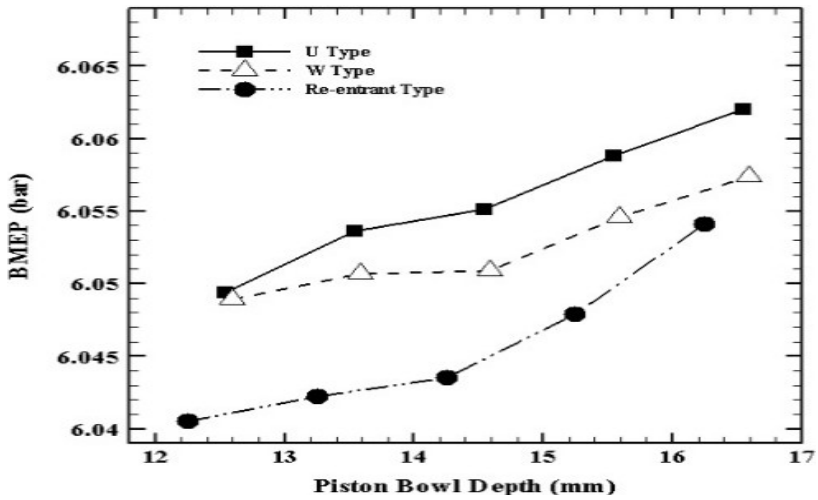

Figure 6: Comparison of BMEP for U type, ω type, and Re-entrant type at different bowl depths

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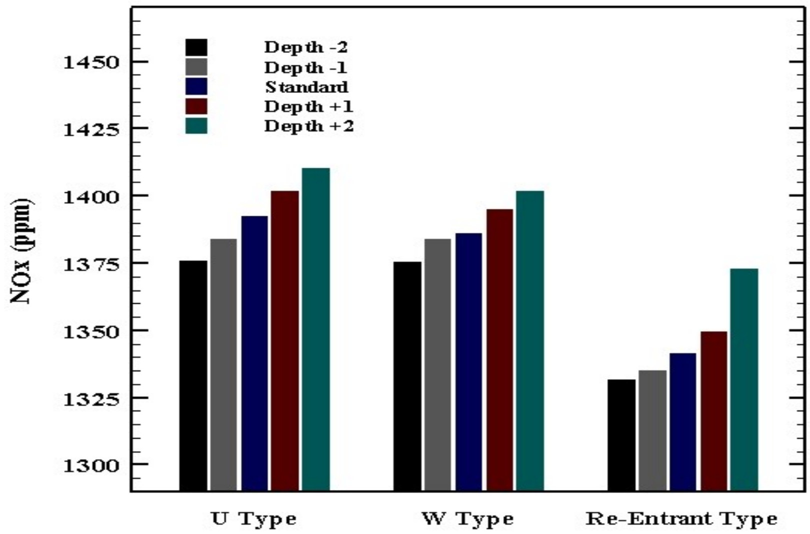

Figure 7: Comparison data between the type of piston bowl of U type, ω type, and Re-entrant type and the emissions of NOx

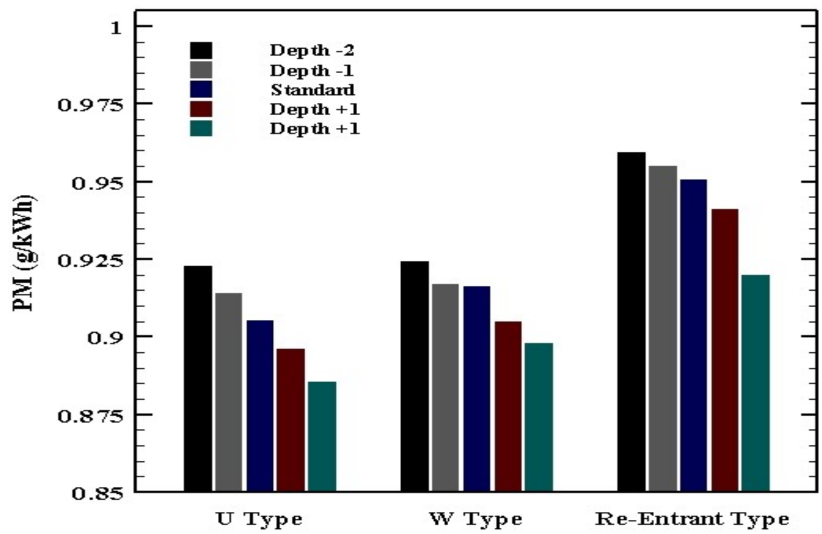

Figure 8: Comparison data between the type of piston bowl of U type, ω type, and Re-entrant type and the emissions of PM

The amounts of NOx increase as the depth of the piston bowl increases in all types. Changes in the depth of the piston bowl also affect the amount of NOx emissions produced. By increasing the depth of the piston bowl, the volume of the combustion chamber will increase and cause air movement to increase, resulting in a better air-fuel mixture. As a result, the cylinder temperature increases [18]. An increase in cylinder temperature will lead to higher NOx emissions, because NOx is generally formed at high temperatures. When cylinder temperatures are lower, NOx emissions are reduced. Therefore, cylinder temperature is a critical factor affecting how NOx is formed inside the engine cylinder [24].

Figure 8 shows the results between piston bowl type and PM emissions at each piston bowl depth variation -2, -1, Standard, +1, and +2. U type produces the lowest PM emissions at depth variation +2 with 0.88546 g/kWh and the highest PM emissions at depth variation -2 with 0.92268 g/kWh. ω type produces the lowest PM emissions at depth variation +2 with 0.89781 g/kWh and the highest PM emissions at depth variation -2 with 0.92417 g/kWh. Re-entrant type produces the lowest PM emissions at depth variation +2 with 0.92008 g/kWh and the highest PM emissions at depth variation -2 with 0.95951 g/kWh. In contrast with previous discussion, the amount of emission of PM is decreasing as increasing of the depth of the piston bowl. The constant decrease as the depth of the piston bowl increases is shown by all piston bowl types. Overall, the highest and lowest producers the PM emissions are Re-entrant and U type, respectively, and the ω type in the middle.

In contrast to NOx, PM emissions increase when the cylinder temperature decreases. Conversely, the higher the temperature in the cylinder, the PM emissions tend to decrease. Meanwhile, low cylinder temperatures help reduce NOx emissions. Therefore, reducing NOx and PM emissions simultaneously is a major challenge. Efforts to lower cylinder temperatures to reduce NOx may lead to an increase in PM emissions, and vice versa. This phenomenon is known as the NOx-PM Trade Off, where NOx and PM will oppose each other [4].

4. CONCLUSION

Engine power, specific fuel consumption, brake mean effective pressure, NOx emissions, and PM emissions measurement are estimated by multifunctional open-source Diesel-RK software under different conditions of type of piston bowl, and depth of piston bowl at constant speed of 2600 rpm and constant fuel of diesel fuel. For a similar depth of piston bowl, the highest to lowest engine power is produced by U type, ω type, and Re-entrant type. The lowest to highest specific fuel consumption is produced by U type, ω type, and Re-entrant type. The highest to lowest brake mean effective pressure is produced by U type, ω type, and Re-entrant type. At nearly the same depth of the piston bowl, the value of NOx emission from highest to lowest is shown by U type, ω type, and Re-entrant, respectively. On the other hand, the PM emissions of Re-entrant, ω type, and U type have the highest to lowest value, respectively. U type at +2 depth showed the best overall performance, with high power output of 5.2816 kW, efficient fuel consumption at 0.25933 kg/kWh, the highest BMEP of 6.0620 bar, and low PM emissions of 0.88546 g/kWh. On the other hand, the Re-entrant type at depth -2 produced the lowest NOx emissions at 1331.5 ppm.

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