Influence of the Port Height to Stroke Ratio on the Performance of an OP2S Engine Fueled with Methanol/Diesel

Wei Yang 1,*, Feng Li 1, Fukang Ma 1, Dan Xu 2, Junfeng Xu 1 and Fang Wang 3

1 School of Energy and Power Engineering, North University of China, University Road No.3, Taiyuan 030051, China; fengli@nuc.edu.cn (F.L.); mfknuc@126.com (F.M.); xjf@nuc.edu.cn (J.X.)
2 China North Engine Research Institute (Tianjin), Tianjin 300400, China; xudan100190@163.com
3 Shanxi Diesel Engine Industry Corporation, Ltd., Datong 037036, China; lihg0101@163.com
* Correspondence: yangwei2184@126.com

Abstract: Zero carbon emission is a mainstream trend in the development of internal combustion engines (ICEs) in the future. ICEs need to constantly surpass the existing working mechanism, especially in order to explore the possibility of new combustion methods. Dual-fuel combustion is a good way to reduce carbon emissions and achieve clean combustion. However, the traditional internal combustion engine is limited by its own structure, restricting its performance improvement. The opposed-piston, two-stroke (OP2S) diesel engine is a potential power system with a high degree of structural adjustability. Therefore, this work attempted to apply methanol/diesel dual-fuel to OP2S engines in order to explore efficient and clean combustion modes in the future. In this work, a one-dimensional simulation model of an OP2S diesel engine was established and verified. The effect of the port height to stroke ratio on the performance of the OP2S diesel engine was mainly studied for different methanol blending ratios. The results show that the methanol blending ratio does not affect the port height to stroke ratio where the optimal values of the MIP and scavenging efficiency appear. The optimal methanol blending ratio for the power performance of OP2S diesel engines is 5~15%. There is a trade-off relationship between the MIP/scavenging efficiency and trapping efficiency. For the optimization of an OP2S methanol–diesel engine, priority should be given to ensuring an optimal MIP and scavenging efficiency, and then to the appropriate consideration of the trapping efficiency.

Keywords: opposed-piston two-stroke; methanol/diesel dual-fuel; height to stroke ratio of ports; scavenging process

1. Introduction

The global transportation industry’s demand for energy has been expanding year by year, and is mainly provided by petroleum-derived liquid fuels to power internal combustion engines (ICEs) [1]. By 2040, global car ownership will double, which will further increase the demand for petroleum-derived fuels, threatening the global environment. In order to solve the environmental crisis, various green power systems are emerging, such as hydrogen fuel cells, etc. It will be difficult for these green power systems to replace the ICEs as the main power system in a short time [2]. The ICEs must continuously improve their fuel economy and power, and reduce emissions. This is a long-term challenge for the internal combustion engine industry in the future.

In order to face the challenge, conventional fuel engines have gradually realized a variety of combustion methods, such as premixed charge compression ignition (PCCI), low-temperature combustion (LTC), and homogeneous charge compression ignition (HCCI), etc., through high-pressure common rail, variable valve phase, EGR, and special combustion chamber structures. Due to the limitations of the physical and chemical properties and combustion mode of hydrocarbon fuels, it is difficult to further improve their thermal efficiency, and a large number of emissions are inevitably generated [3]. This means that...
new methods must be explored in terms of fuel characteristics. The traditional hydrocarbon fuel itself does not contain oxygen, and it is difficult to ensure that all of the carbon atoms are combined with the corresponding oxygen atoms. This means that more air is required to burn the fuel, and soot is produced, as well as more carbon dioxide emissions. This status is in great conflict with the trend of existing environmental protection. At the 21st United Nations Climate Change Conference, countries reached a consensus: control the global average temperature rise to within 2 °C of its value before industrialization, achieve the goal of global carbon neutrality from 2050 to 2100, and subsequently develop their schedule of carbon neutrality [4].

The achievement of carbon neutrality and zero emissions from internal combustion engines is a beautiful vision. The internal combustion engine itself needs to be continuously upgraded in order to adapt to the new trend of industrial development and environmental protection. This triggered the appearance of the dual-fuel combustion mode of adding other clean and renewable fuels to diesel [5,6], such as natural gas and biodiesel, etc. This combustion method can effectively improve the combustion efficiency and reduce emissions due to the ability to adjust and produce a variety of combustion methods. In these fuels, methanol is widely applied because of its wide array of sources. It can be derived from traditional energy or renewable energy [7]. Cenk Sayin et al. studied the power and emission characteristics of the DI diesel engine with different methanol blending ratios [8]. The results showed that NO\textsubscript{x} emissions increased slightly, but smoke opacity, CO and UHC emissions decreased dramatically through the addition of methanol to the fuel blend. Ganesh Duraisamy et al. studied the effect of methanol/diesel reactivity controlled compression ignition (RCCI) combustion in a three-cylinder engine [9]. The results showed that an increased methanol premixed mass fraction has a considerable effect on the combustion and emissions of an RCCI engine for both methanol/diesel combinations. Chunde Yao et al. investigated the combustion and emission characteristics of a dual-fuel diesel engine with a high premixed ratio of methanol [10]. The results showed that the trade-off relationship between NO\textsubscript{x} and soot emissions disappeared.

In conclusion, a methanol/diesel dual-fuel has shown good advantages over traditional internal combustion engines. However, little research has focused on the application of dual-fuels in opposed-piston, two-stroke (OP2S) diesel engines.

The OP2S diesel engine has attracted attention due to its simple structure, high power density, high thermal efficiency, and low heat transfer loss [11,12]. Jean-Pierre Pirault and Martin Flint pointed out that compared with engines of the same volume, the inherent characteristics of the OP2S diesel engine show strong operating and cost advantages, which are very suitable for the future demand for high-performance engines [13–15]. Therefore, the use of new technology to research OP2S diesel engines has good development prospects to overcome its disadvantages, and thus to achieve high-efficiency and low-emission combustion. The use of methanol/diesel dual-fuel on the OP2S engines may be able to meet the needs of future internal combustion engines for efficient and clean combustion.

In order to explore the potential of methanol/diesel dual-fuel technology for an OP2S diesel engine, an equivalent method was applied to establish the GT-POWER model of the OP2S diesel engine. The present work mainly analyzes the IMPE, scavenging efficiency, and trapping efficiency of the OP2S diesel engine under different methanol ratios in order to promote the application of methanol/diesel dual-fuel technology in OP2S diesel engines.

2. Simulation Model and Validation

The simulation was conducted using GT-POWER version 2016 software. As there was no OP2S cylinder module in GT-POWER, the two-stroke diesel engine model was applied to simulate the working process of an OP2S diesel engine by an equivalent method. In the equivalent model, the position at the minimum volume was defined as the inner dead center (IDC), and the position at the maximum volume was defined as the outer dead center (ODC). The parameters of the OP2S diesel engine are shown in Table 1. The simulation of the OP2S diesel engine contained the scavenging process and combustion
process. Through the combination of the 1D/3D simulations and the flow experiment, we acquire the scavenging curves and the discharge coefficient, as shown in Figure 1. Then, both parameters were respectively substituted into the 1D simulation model of the first stage in order to obtain the final simulation model. A detailed description of modeling and validation can be found in [16].

Table 1. Parameters of the OP2S diesel engine.

| Parameter               | Value   |
|-------------------------|---------|
| Bowl/mm                 | 85      |
| Stock/mm                | 2 × 90  |
| Compression ratio       | 22      |
| Intake temperature/K    | 320     |
| Intake pressure/MPa     | 0.13    |
| Back pressure /MPa      | 0.1     |
| Rated speed/r/min       | 3000    |
| Cycle fuel injection/mg/cycle | 36     |

Figure 1. Validation of a 1D simulation model.

3. Results and Discussion

3.1. The Influence of the Intake Port

Figure 2 shows the mean indicated pressure (MIP) under different height to stroke ratios of intake ports. With the increase of the height to stroke ratio of the intake port, the MIP first increases and then decreases. When the height to stroke ratio of the intake port is less than 0.056, the MIP increases linearly. Because a small intake port height results in a small inlet airflow, the air entering the cylinder can be quickly mixed with the fuel. When the height to stroke ratio of the intake port is greater than 0.056, the MIP increases slowly. Because a large enough intake port causes enough air to enter the cylinder, fuel and air mixing dominates the combustion performance. When the height to stroke ratio of the intake port is greater than 0.13, the MIP decreases slowly. Because the increase of the methanol blending ratio, when the height to stroke ratio...
of the intake port is less than 0.056, the MIP curves under different ratios basically overlap; when the height to stroke ratio of the intake port is greater than 0.056, the increase of the methanol blending ratio results in a uniform decreasing trend for the MIP under different methanol ratios. The MIP decreases by around 1.9% for every 5% increase in the blending ratio. However, the height to stroke ratio of the intake ports at the greatest MIP still remains 0.13 for different blending ratios.

![Figure 2. MIP for different height to stroke ratios of intake ports.](image)

Figure 3 shows the scavenging efficiency for different height to stroke ratios of intake ports. With the increase of the height to stroke ratio of the intake port, the scavenging efficiency first increases and then decreases. When the height to stroke ratio of the intake port is less than 0.056, the scavenging efficiency increases linearly. Because a small intake port height results in a small inlet airflow, the air can be completely enclosed in the cylinder. When the height to stroke ratio of the intake port is greater than 0.056, the scavenging efficiency increases slowly. Because an increase of the intake port height results in a large inlet airflow, part of the charge will flow into the exhaust manifold. When the height to stroke ratio of the intake port is greater than 0.13, the scavenging efficiency decreases slowly. Because the increase of intake port height results in a long intake time, part of the charge will flow into the intake manifold. With the increase of the methanol blending ratio, when the height to stroke ratio of the intake port is less than 0.056, the scavenging efficiency curves under different ratios basically overlap. When the height to stroke ratio of the intake port is greater than 0.056, the increase of the methanol blending ratio results in a uniform increasing trend for the scavenging efficiency under different ratios. The scavenging efficiency is increased by around 2.2% for every 5% increase in the blending ratio. The height to stroke ratio of the intake ports at the greatest scavenging efficiency still remains 0.13 for different blending ratios. The more methanol will lower the in-cylinder pressure, increasing the scavenging pressure difference and enclosing more air in the cylinder.

Figure 4 shows the trapping efficiency for different height to stroke ratios of the intake ports. The increase of the height to stroke ratio of the intake port results in a decrease in the trapping efficiency. This is because the increase of the height to stroke ratio of the intake port will increase the inlet airflow and the scavenging time (the overlap period between intake and exhaust periods), thereby increasing the overflow of fresh charge. With the increase of the methanol blending ratio, the trapping efficiency showed a decreasing trend. This is because the MIP decreases with the increase of the methanol mixing ratio. The pressure in the cylinder is lower when the exhaust port opens, decreasing the air in the free
exhaust period (only the exhaust port opens). The fresh air sealed in the cylinder decreases during the scavenging process.

Figure 3. Scavenging efficiency for different height to stroke ratios of the intake ports.

Figure 4. Trapping efficiency for different height to stroke ratios of the intake ports.

3.2. The Influence of the Exhaust Port

Figure 5 shows the MIP for different height to stroke ratios of the exhaust ports. With the increase of the height to stroke ratio of the exhaust port, the MIP first increases and then decreases. When the height to stroke ratio of the exhaust port is less than 0.08, the MIP increases linearly. The increase of the exhaust port height is beneficial to the discharge of the residual exhaust gas in the cylinder, thereby promoting combustion. After the height to stroke ratio of the exhaust port is greater than 0.08, the MIP decreases slowly. Because the increase of the exhaust port height will increase the scavenging time, more fresh charge will discharge with the exhaust gas, thereby deteriorating the combustion. The MIP increases slightly with increasing methanol ratio. This is mainly because methanol contains oxygen,
When the height to stroke ratio of the exhaust port is greater than 0.08, the scavenging port height results in less exhaust gas, there are a small number of fresh charge overflows. When the height to stroke ratio of the exhaust port is less than 0.08, the scavenging efficiency increases linearly. Because the small exhaust ports promote combustion, but the low calorific value of methanol restricts the substantial increase in MIP. The maximum MIP for different methanol ratios appears to be 0.11.

Figure 5. MIP for different height to stroke ratios of exhaust ports.

Figure 6 shows the scavenging efficiency for different height to stroke ratios of the exhaust ports. With the increase of the height to stroke ratio of the exhaust port, the scavenging efficiency gradually increases. When the height to stroke ratio of the exhaust port is less than 0.08, the scavenging efficiency increases linearly. Because the small exhaust port height results in less exhaust gas, there are a small number of fresh charge overflows. When the height to stroke ratio of the exhaust port is greater than 0.08, the scavenging efficiency increases slowly. After the height to stroke ratio of the exhaust port is increased to 0.11, the scavenging efficiency remains constant. With the increase of the exhaust port height, the increase of the methanol ratio has little effect on the scavenging efficiency.

Figure 6. Scavenging efficiency for different height to stroke ratios of the exhaust ports.
Figure 7 shows the trapping efficiency for different height to stroke ratios of the exhaust ports. With the increase of the height to stroke ratio of the exhaust port, the trapping efficiency shows a decreasing trend. Because the increase of the exhaust port height will increase the inlet airflow and the scavenging time, the overflow of the fresh charge will increase. With the increase of the exhaust port height, the increase of the methanol ratio has little effect on the trapping efficiency.

3.3. The Interaction of the Intake and Exhaust Ports

Figure 8 shows the MIP for the interaction of the intake and exhaust ports. At the same exhaust port height, the MIP will first increase and then decrease with the increase of intake port heights. The smaller intake port height will reduce intake air and the larger intake port height will reduce the effective compression ratio. At the same intake port height, the MIP will also first increase and then decrease with the increase of intake port heights. The smaller exhaust port height will retain more residual gas in the cylinder and the larger exhaust port height will reduce the effective compression ratio. When the height to stroke ratio of the intake port is 0.13 and the height to stroke ratio of the exhaust port is 0.17, the optimal MIP (the blue star) appears. The increasing methanol blending ratio will decrease the height to stroke ratio of ports for the optimal MIP. With the increase of the methanol blending ratio, the region with an MIP greater than 6.5 bar only appears in the condition of M0. When the methanol blending ratio is less than 15%, the region with an MIP greater than 6 bar keeps constant. When the methanol blending ratio is greater than 15%, the region with an MIP greater than 6 bar decrease dramatically. This indicates that the blending of methanol in diesel will reduce the power performance of the OP2S diesel engine. When the blending ratio is 5–15%, the power performance of the OP2S diesel engine still maintains a high level.

Figure 9 shows the scavenging efficiency for the interaction of the intake and exhaust ports. At the same exhaust port height, the scavenging efficiency will first increase and then decrease with the increase of intake port heights. The smaller intake port height will reduce intake air and the larger intake port height will result in the overflow into the intake manifold. At the same intake port height, the scavenging efficiency will also first increase and then decrease with the increase of intake port heights. The smaller exhaust port height will lead to a small pressure difference and the larger exhaust port height will result in the overflow into the exhaust manifold. The increasing methanol blending ratio will have no significant effect on the height to stroke ratio of ports for the optimal scavenging efficiency (the blue star). With the increase of the methanol blending ratio, the region with a scavenging efficiency greater than 0.9 gradually increases. The greatest
scavenging efficiency in the condition of M0 does not exceed 0.9. When the methanol blending ratio is less than 5%, the region with a scavenging efficiency greater than 0.8 increases obviously. When the methanol blending ratio is greater than 15%, the region with a scavenging efficiency greater than 0.8 bar decreases slightly.

Figure 8. MIP for the interaction of the intake and exhaust ports.

Figure 9 shows the scavenging efficiency for the interaction of the intake and exhaust ports. At the same exhaust port height, the scavenging efficiency will first increase and then decrease with the increase of intake port heights. The smaller intake port height will reduce intake air and the larger intake port height will result in the overflow into the intake manifold. At the same intake port height, the scavenging efficiency will also first increases and then decreases with the increase of intake port heights. The smaller exhaust port height will lead to a small pressure difference and the larger exhaust port height will result in the overflow into the exhaust manifold. The increasing methanol blending ratio
will have no significant effect on the height to stroke ratio of ports for the optimal scavenging efficiency (the blue star). With the increase of the methanol blending ratio, the region with a scavenging efficiency greater than 0.9 gradually increases. The greatest scavenging efficiency in the condition of M0 does not exceed 0.9. When the methanol blending ratio is less than 5%, the region with a scavenging efficiency greater than 0.8 increases obviously. When the methanol blending ratio is greater than 15%, the region with a scavenging efficiency greater than 0.8 bar decreases slightly.

Figure 9. Scavenging efficiency for the interaction of the intake and exhaust ports.

Figure 10 shows the trapping efficiency for the interaction of the intake and exhaust ports. When the height to stroke ratio of the intake ports is large, and the height to stroke ratio of the exhaust ports is small, the scavenging efficiency is largest. The larger intake port height will increase the intake air accelerating the replacement of exhaust gas and the
smaller exhaust port height will enhance exhaust resistance preventing fresh charge from overflowing. The increasing methanol blending ratio has little effect on the distribution of trapping efficiency. With the increase of the methanol blending ratio, the region with a trapping efficiency less than 0.6 increases slightly. The region with a trapping efficiency greater than 0.9 has no significant change. Combining Figures 8 and 9, it can be seen that there is a trade-off relationship between the MIP/scavenging efficiency and trapping efficiency. This indicates that the OP2S diesel engine should consider the trapping efficiency after optimizing the MIP and scavenging efficiency of the OP2S diesel engine.

Figure 10. Trapping efficiency for the interaction of the intake and exhaust ports.
4. Conclusions

Compared with the exhaust port parameters, the methanol blending ratio has a greater impact on the MIP, scavenging efficiency, and trapping efficiency of the OP2S diesel engine for different intake port parameters. When the height to stroke ratio of the intake port is less than 0.056, the MIP and scavenging efficiency curves overlap for different methanol blending ratios; when the height to stroke ratio of the intake port is greater than 0.056, the MIP is reduced evenly for different methanol blending ratios, while the scavenging efficiency shows a uniform increasing trend. The methanol blending ratio does not affect the optimal values of the MIP and scavenging efficiency. For different intake parameters, the trapping efficiency shows a uniform decreasing trend with the increase of the methanol blending ratio.

For the interaction of the intake and exhaust ports, when the height to stroke of the intake and exhaust ports are relatively larger, the MIP and scavenging efficiency will be the optimal value. Furthermore, the increasing methanol blending ratio will decrease the height to stroke ratio of ports for the optimal MIP. But the increasing methanol blending ratio has no significant effect on the height to stroke ratio of ports for the optimal scavenging efficiency. The blending of methanol in diesel will reduce the power performance of OP2S diesel engines. Without lowering the power performance of the OP2S diesel engine, the optimal methanol blending ratio is 5%~15%.

When the height to stroke of the intake port is relatively large and the height to stroke of the exhaust port is relatively small, the trapping efficiency is large. When the height to stroke of the intake port is relatively small and the height stroke of the exhaust port is relatively large, the trapping efficiency is small. There is a trade-off relationship between the MIP/scavenging efficiency and trapping efficiency. When optimizing the OP2S engine fueled with methanol/diesel, it is necessary to give priority to ensuring the optimal MIP and scavenging efficiency, and then to properly consider the trapping efficiency. Besides, the increasing methanol blending ratio has little effect on the distribution of trapping efficiency.

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Acronyms

DI direct injection
HCCI homogeneous charge compression ignition
MIP mean indicated pressure
ICEs internal combustion engines
IDC inner dead center
LTC Low-temperature combustion
ODC outer dead center
OP2S opposed-piston two-stroke
PCCI premixed charge compression ignition
RCCI reactivity controlled compression ignition
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