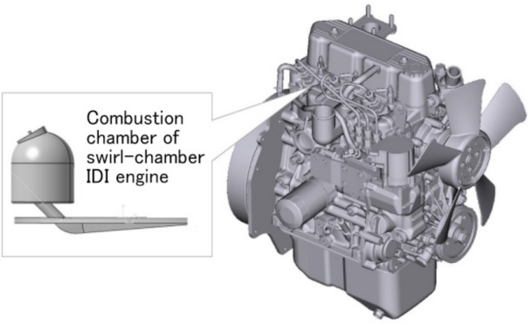
Combustion Chamber Shape Optimization for Small Diesel Engines by Coupling CFD and AI



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Swirl-chamber indirect injection engines are widely used as small diesel engines for industrial applications. In order to improve the commercial potential of our products, Mitsubishi Heavy Industries Engine & Turbocharger, Ltd. (MHIET) has applied an optimization design process coupling CFD (Computational Fluid Dynamics) and AI (Artificial Intelligence) to the combustion chamber shape of swirl-chamber indirect injection engines for the first time. After defining the combustion and flow concepts for a swirl-chamber indirect injection engine, we coupled CFD and AI to automatically search for the optimal combustion chamber shape. Through analysis of the data obtained in the searching process, we selected the optimal combustion chamber shape and also confirmed that performance improvement was achieved as expected by actual equipment testing. In addition, by applying the optimized combustion chamber to the new L series engine under development, it was verified that the output range can be significantly expanded compared to an existing engine, while achieving a class-leading brake mean effective pressure (BMEP) and specific fuel consumption.

1. Introduction

Diesel engines are used in a wide range of applications, including automobiles, ships, construction machinery, agricultural machinery, and power generators, due to their characteristics such as high power density. Among diesel engines, swirl-chamber indirect injection (IDI) engines have an advantage over direct injection (DI) engines in that they form a strong flow in the combustion chamber, allowing for a higher power density while employing a less expensive fuel injection system. This advantage matches the market demand for small industrial engines that require low cost and high power density, thus swirl-chamber IDI engines have been widely used from the past to the present. On the other hand, as model-based development has been spreading in recent years, technologies such as three-dimensional computational fluid dynamics (CFD) and optimization technology (AI) have been well accepted in the design field, but there have been few cases in which these technologies are applied to swirl-chamber IDI engines. As such, we have developed a design process to apply these model-based technologies to optimize the shape of the combustion chamber of a swirl-chamber IDI engine. In addition, we applied the optimized combustion chamber to the new L series engine under development, aiming to expand its output range and achieve class-leading performance.

2. Combustion chamber shape designing process

2.1 Combustion and flow concepts

Our optimization goal is to achieve low emissions and low specific fuel consumption. **Figure 1** shows the combustion and flow concepts. In general, it has been shown that the combustion rate of swirl-chamber IDI engines is represented by two peaks, with the first half

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corresponding to the sub chamber combustion and the second half to the main chamber combustion. In terms of low emissions, it is necessary to advance the end of combustion while retarding the center of gravity of combustion in order to reduce NOx and soot at the same time. Specifically, we propose a combustion concept that suppresses sub chamber combustion and activates main chamber combustion to obtain the ideal combustion rates. In order to control combustion in diesel engines, which are mixture rate-limiting, it is necessary to control the flow. Therefore, we considered that low emissions could be achieved by suppressing the sub chamber flow to reduce sub chamber combustion and enhancing the main chamber flow to activate main chamber combustion. Next, in terms of lower specific fuel consumption, it has been shown that most of the cooling losses in swirl chamber IDI engines occur in the sub chamber. Therefore, we considered that reducing the sub chamber flow would lead to a reduction in the heat transfer coefficient and, consequently, to the achievement of lower specific fuel consumption. From the above, a flow concept in which the flow in the sub chamber and main chamber is intentionally made stronger or weaker was derived, starting from the combustion concept. Two flow parameters were also selected as objective functions in the optimization: reduction of sub chamber velocity and increase of main chamber velocity.

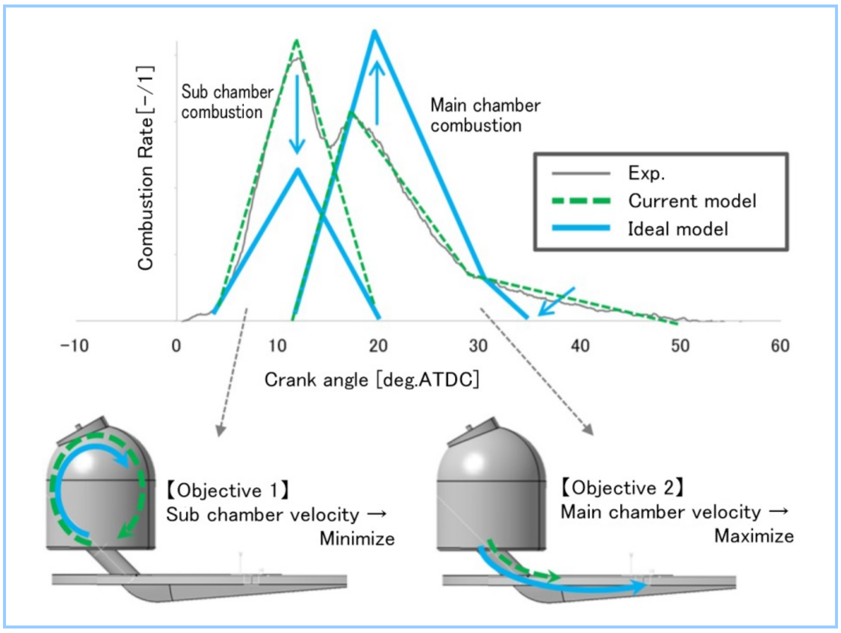


Figure 1 Ideal combustion definition and flow concept

2.2 Optimization process

Figure 2 shows the process of optimizing the combustion chamber shape using CFD and AI. Conventionally, CFD was considered unsuitable for optimization due to its high computational cost, but combining it with AI allows for an improved trade-off between computational cost and accuracy. In this study, parametric optimization was applied as the method for optimizing the shape. First, as shown in **Figure 3**, the combustion chamber shape was expressed using seven parameters, vari1 to vari7. Next, 200 sets of initial combustion chamber shapes were generated by randomly combining the seven parameters using a design of experiment (DOE) method. CFD analysis was performed on each shape, and the correlation between the design variables and the objective function was organized using a neural network. By using a genetic algorithm on the obtained correlations, optimization was performed to generate a combustion chamber shape for the next step. These processes were repeated several times to make a total of 300 calculations to automatically search for the optimum combustion chamber shape.

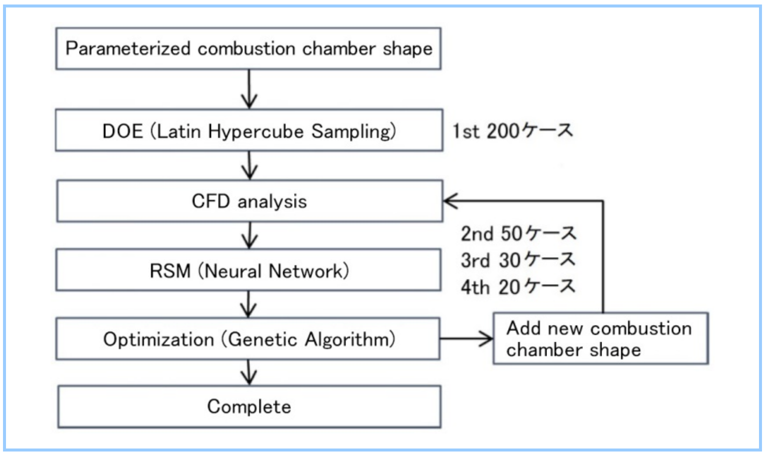


Figure 2　Optimization process

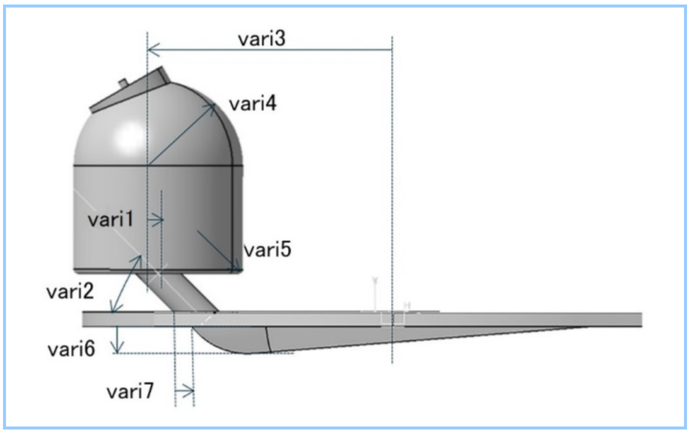
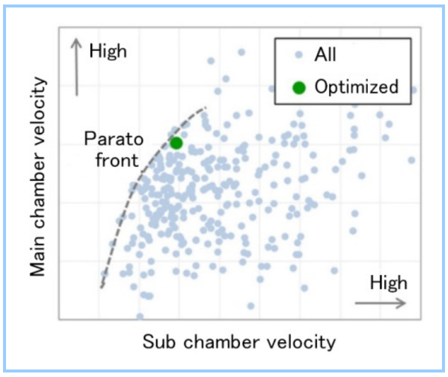


Figure 3　Parametric shape optimization

2.3　Optimization result

Figure 4 shows a scatter plot of the objective function after a total of 300 calculations were made, and **Figure 5** shows the result of sensitivity analysis of the design variables with respect to the objective function. Figure 5 indicates that suppression of the sub chamber flow is highly sensitive to vari5 (sub chamber bottom corner radius) and that vari7 (cavity offset) should be the design target for enhancement of the main chamber flow. Through data analysis, we were able to grasp rate-limiting design variables for efficient phenomenon control and selected an optimal shape with the above two characteristics from the vicinity of the Pareto solution shown in Figure 4.



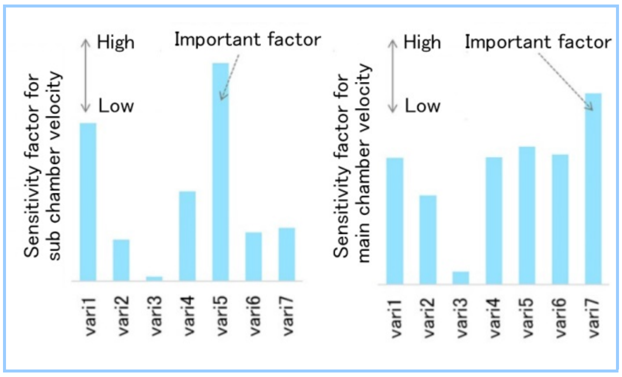


Figure 4　Pareto performance

Figure 5　Sensitivity factor for each objective

2.4　Knowledge accumulation

In order to grasp the physical meaning of the solutions obtained in the optimization and to acquire useful knowledge for the design, the effects of changing the two rate-limiting design variables extracted above were verified by CFD analysis.

(1)　Suppression of sub chamber flow

Figure 6 shows the result of CFD analysis at the top dead center when vari5 (sub chamber bottom corner radius) is varied. From this result, it can be considered that reducing the sub chamber bottom corner radius leads to repeated expansion and contraction of the flow near the sub chamber bottom corner radius, thereby suppressing the sub chamber flow.

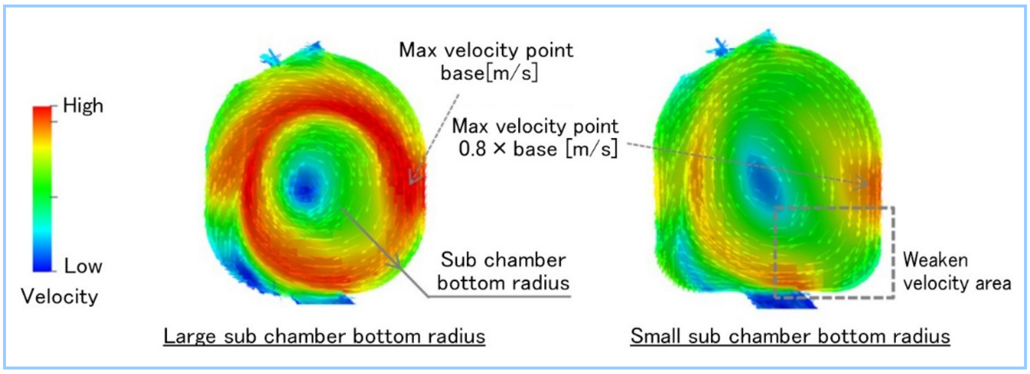


Figure 6 CFD results of sub chamber bottom radius effect

(2) Enhancement of main chamber flow

Figure 7 shows the result of CFD analysis during the expansion stroke when vari7 (cavity offset) is varied. From this result, it can be considered that increasing the cavity offset suppresses the separation of flow from the nozzle to the cavity thereby enhancing the main chamber flow.

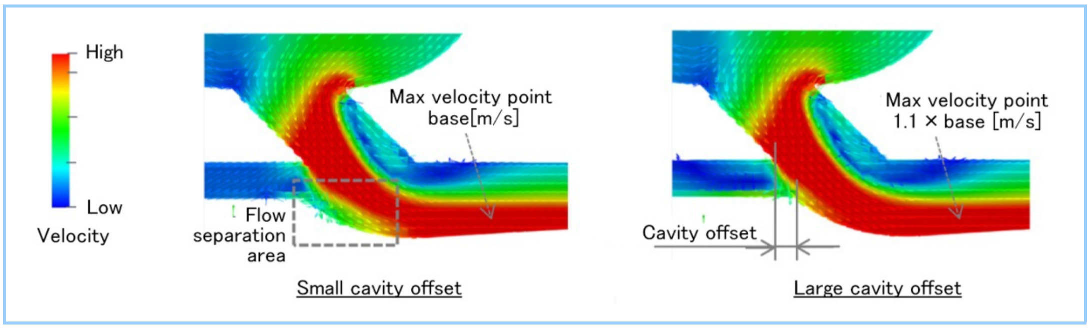


Figure 7 CFD results of cavity offset effect

3. Verification result

3.1 Performance comparison between new and current products

Figure 8 compares the performance of the new L series engine under development to which the optimized combustion chamber was applied with that of the conventional engine. It was found that the new L series engine achieved a soot reduction of 80% in the targeted high-load region, a NOx reduction of 15% in the low-to-medium load region, which is the center of gravity in the exhaust gas measurement mode, and an improvement in the rated specific fuel consumption of 5%. The optimized combustion chamber showed the performance improvement as expected, confirming the validity of the design process. By optimizing the combustion chamber shape, both low emissions and low specific fuel consumption were achieved.

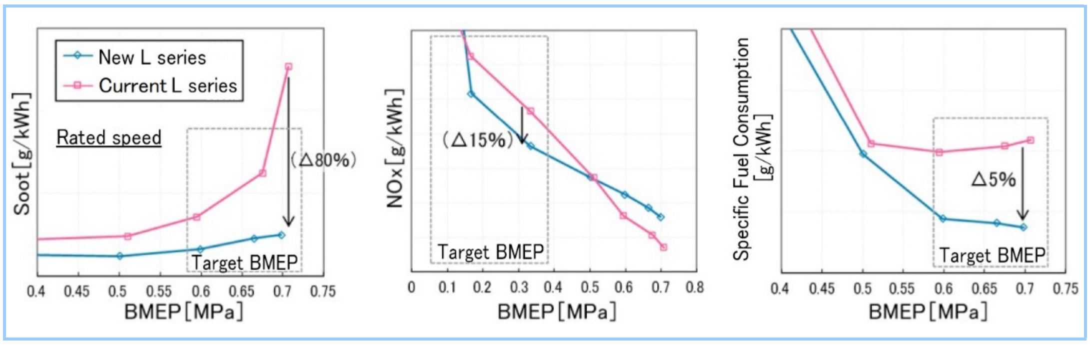


Figure 8 Test results

3.2 Expansion of output range of new L series engine

The new L series engine with optimized combustion chamber shape has greatly improved exhaust gas performance in high-load regions, thus expanding the output range that can comply with EPA(U.S. Environmental Protection Agency)-Tier 4 regulations for North America. **Figure 9** shows the result of comparing the rated power ranges of the new and current L series engines. Whereas the conventional L series engine could handle up to 13.2 kW, the new L series engine is expected to be able to handle up to 18.4 kW, while maintaining a similar footprint and cost. It is also expected that the new L series engine will be able to comply with European and Japanese regulations.

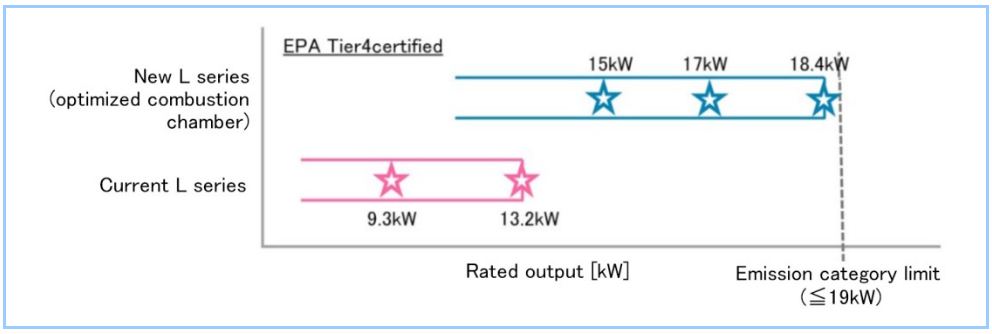


Figure 9 Rated output range of new L series engine

3.3 Performance comparison with competitor engines

Figure 10 compares the brake mean effective pressure (BMEP) and rated specific fuel consumption of the new L series engine with those of all other swirl-chamber IDI engines submitted to the EPA[1]. It was confirmed that the new L series engine with the optimized combustion chamber can achieve class-leading BMEP and rated specific fuel consumption.

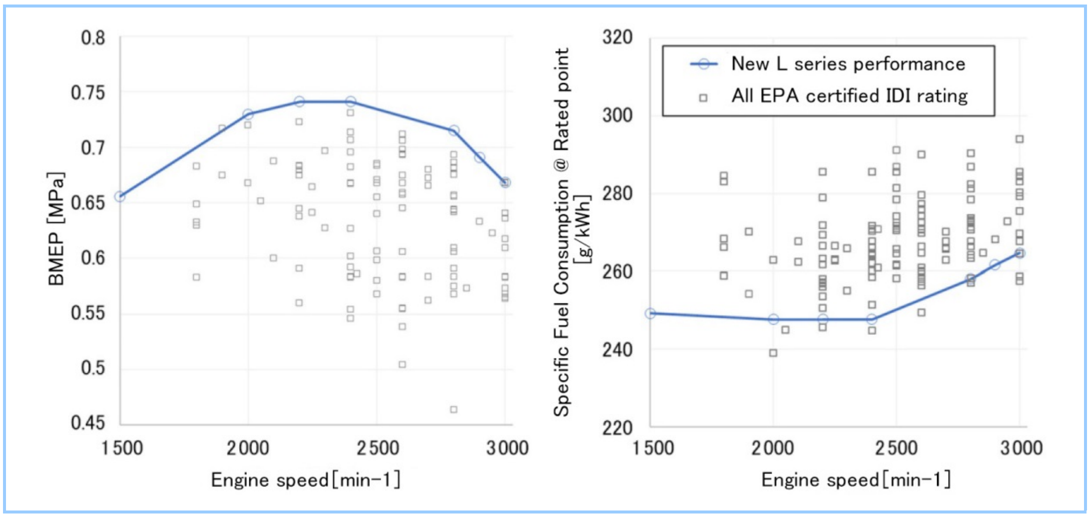


Figure 10 Performance comparison

4. Conclusion

We defined the combustion and flow concepts for swirl chamber IDI engines and coupled CFD and AI, thereby optimizing the combustion chamber shape. We applied the optimized combustion chamber to the new L series engine under development and confirmed that it can achieve significantly lower emissions and lower specific fuel consumption compared to an existing model. Moreover, the output range was greatly expanded to the high output side and the lineup was expanded, while maintaining a similar footprint and cost equivalent to those of existing models. Finally, through the performance comparison with competitor engines, we have confirmed that the new engine achieves class-leading BMEP and specific fuel consumption. The new L series engine is currently under development and evaluation, and is planned to be launched in the market by the end of 2023.

MHIET, as a key player in energy supply, will develop decarbonized engines applying state-of-the-art technologies, such as hydrogen engines, to achieve a carbon-neutral society. We will also work toward the achievement of a low-carbon society in parallel by improving the performance of existing engines.

References

(1) United States Environmental Protection Agency, Annual Certification Data (2020), https://www.epa.gov/compliance-and-fuel-economy-data/annual-certification-data-vehicles-engines-and-equipment