

A study on Optimization of Combustion Chamber Geometry in Large Diesel Engines Using CFD and Machine Learning

—Analysis of the optimal shape that reflects the design intent—

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To achieve carbon neutrality by 2050, internal combustion engines must simultaneously improve thermal efficiency and reduce emissions, making combustion chamber optimization an effective approach. Traditionally, three-dimensional computational fluid dynamics (3D-CFD) has been employed for this evaluation; however, the increasing computational cost associated with sophisticated simulation models poses a challenge, making it difficult to rapidly perform the extensive parameter searches essential for multi-objective optimization.

In our previous study, an optimization method combining an Artificial Neural Network (ANN) and Particle Swarm Optimization (PSO) was proposed, and optimal combustion chamber geometry candidates were extracted for a diesel engine. Furthermore, 3D-CFD validation confirmed the potential for improving indicated thermal efficiency and reducing emissions. The objective of this study is to elucidate the mechanisms underlying the performance improvements achieved by these optimal geometries through numerical thermal-fluid dynamics evaluations. Specifically, in-cylinder flow, temperature distribution, equivalence ratio distribution, and soot formation behavior were analyzed to investigate the factors contributing to increased thermal efficiency and reduced emissions.

The calculation conditions in this study were an engine speed of 1080 rpm, a medium-load condition (IMEP = 1.4 MPa), and diesel fuel as the test fuel. Compared to BASE, Type 1 showed an increase in indicated thermal efficiency by 0.80 pt, alongside reductions in soot and NOx emissions by 59.8% and 13.1%, respectively. Meanwhile, Type 2 demonstrated a 3.09 pt increase in indicated thermal efficiency and an 82.6% reduction in soot emissions, although NOx emissions increased by 4.70%.

Figure 1 shows a comparison of in-cylinder pressure and heat release rate between BASE and the two optimal combustion chamber geometries. The timings at which cumulative heat release reached 5%, 50%, and 95% were 4.40, 11.39, and 35.12 deg. ATDC for BASE; 4.21, 11.65, and 36.15 deg. ATDC for Type 1; and 3.76, 11.47, and 27.59 deg. ATDC for Type 2, respectively. While no significant difference was observed in the combustion center, Type 2 exhibited a substantial shortening of the combustion duration after 50% heat release, confirming an earlier convergence of heat release in the late combustion phase. This shorter combustion duration is considered to have contributed to reduced heat release during the latter half of the expansion stroke and improved indicated thermal efficiency.

Figure 2 shows the histories of wall heat loss and near-wall gas temperature for BASE and the two optimal combustion chamber geometries. Wall heat loss increased rapidly following the rise in in-cylinder pressure after the onset of combustion. Compared to BASE, peak wall heat loss increased in Type 1 and Type 2, with Type 2 maintaining high values even during the expansion stroke. Furthermore, across all combustion chamber geometries, wall heat loss peaked at approximately 12 deg. ATDC, earlier than the peak near-wall gas temperature occurring at approximately 25 deg. ATDC. This indicates that wall heat loss variation cannot be explained solely by the gas-wall temperature difference, but was also strongly influenced by changes in the heat transfer coefficient driven by near-wall flow velocity and turbulence. In Type 2 in particular, modifications to the combustion chamber geometry altered squish- and spray-induced flows, increasing the velocity gradient near the wall, which likely enhanced convective heat transfer. Additionally, the near-wall gas temperature in Type 2 remained higher than BASE throughout the combustion period, which also contributed to the increased wall heat loss during the expansion stroke.

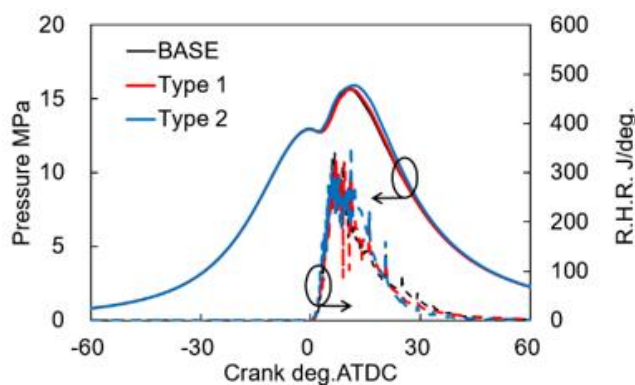


Fig.1 Comparison of cylinder pressure and rate of heat release for two optimized chamber shapes

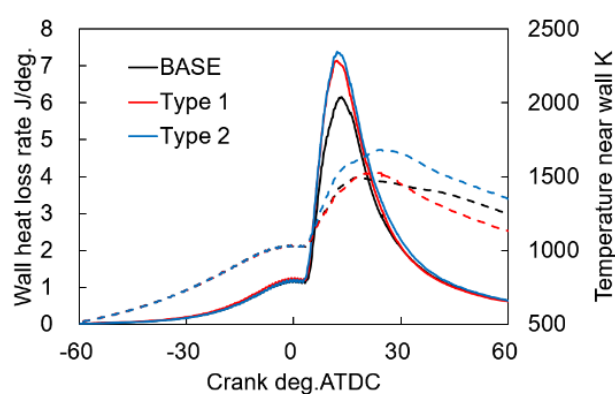


Fig.2 Comparison of wall heat transfer rate and temperature near wall for two optimized chamber