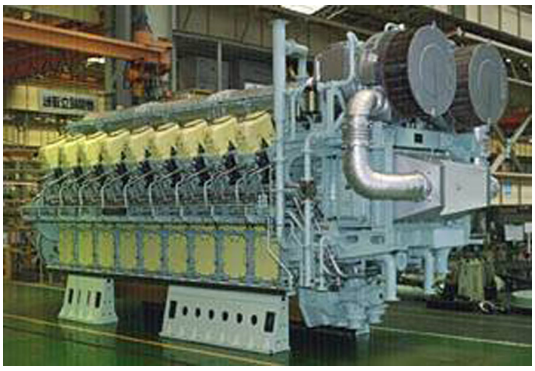
Combustion Simulations Contributing to the Development of Reliable Low-Emission Diesel Engines



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Mitsubishi Heavy Industries, Ltd. (MHI) has been developing simulation technology to attain a reasonable preliminary survey to optimize the combustion chamber shape and fuel injection parameters of a wide variety of diesel engines. MHI has developed a less mesh-dependency spray model, in collaboration with the University of Wisconsin, and compared the results attained with measured values from actual engines. The pressures in the combustion chamber and exhaust gas were predicted at a power output ranging from 10 to 80,000 kW. The efficiency of new engines in development can be promoted using MHI's latest optimization techniques.

1. Introduction

Mitsubishi Heavy Industries, Ltd. (MHI) has improved the combustion in diesel engines by optimizing the shape of the combustion chamber and introducing a common rail injection system, which controls multiple injections and the timing to meet strengthened exhaust gas regulations and lower fuel consumption requirements. Accordingly, the number of design parameters has increased. Reducing the number of parameters that need to be tested by utilizing simulations has therefore become important when developing new engines. MHI has been developing a combustion model that provides highly accurate calculations of the exhaust gas and fuel consumption. Recent modeling developments have focused on the fuel injection plume movement and chemical reactions, in collaboration with the University of Wisconsin in the United States (US), which possesses a high level of diesel combustion simulation technology. This paper describes our model verification process, making use of a small agricultural engine (50-kW class), a mid-sized generator engine (8,000-kW class), and a large marine engine (30,000-kW class), and indicates the effectiveness of our model in the development process for new engines.

2. Outline of Diesel Combustion Simulations

Diesel engine combustion chamber processes consist of the air intake, compression, fuel injection, evaporation, mixing of fuel and air, combustion, exhaust gas generation, expansion, and exhaust, as shown in **Figure 1**. These processes are repeated continuously. The engine power is obtained by transforming the cylinder pressure generated by this series of processes into piston reciprocal movement. The fuel consumption and emissions are affected by moment-to-moment changes of the in-cylinder conditions. The high-temperature gas in the combustion chamber is the main factor of heat stress, which must be considered to design a reliable engine. As a result, proper understanding and optimization of the series of processes described above is important in developing a highly reliable engine with low emissions.

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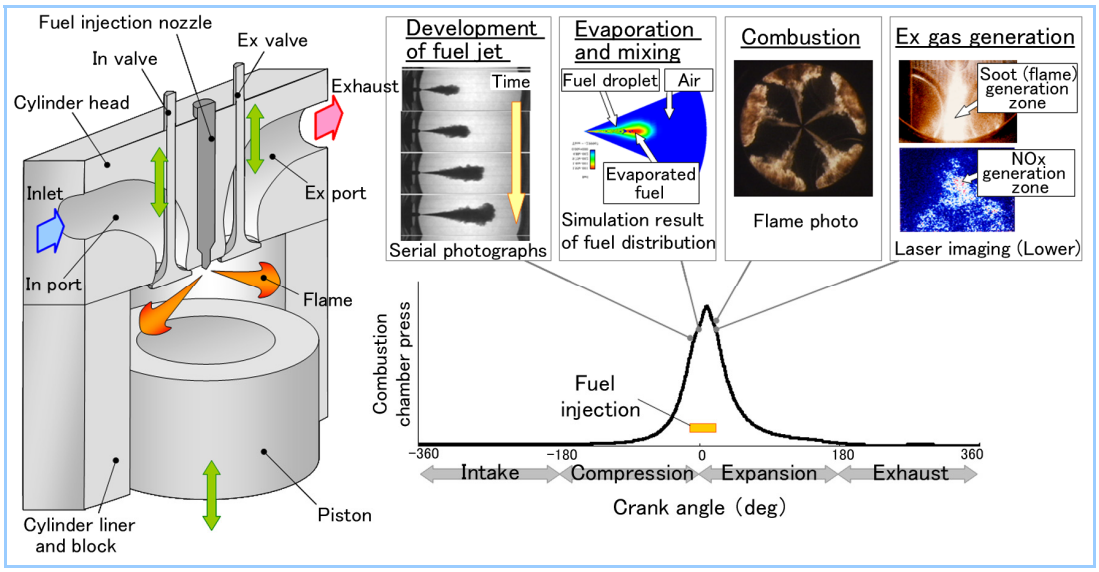

Figure 1 Processes in a diesel engine combustion chamber

Our diesel simulation (**Figure 2**) incorporates a model to calculate the series of processes described above based on computational fluid dynamics (CFD) and determines the moment-to-moment in-cylinder conditions, including the temperature, pressure, and distributions of gas species, in the combustion chamber. The modeling of the fuel spray movement and chemical reactions, which will significantly affect the combustion, is being developed collaboratively with the University of Wisconsin, which possesses ample fundamental test data and model development technology. The development is mainly focused on reducing the mesh size dependency, allowing good simulation results regardless of the analysis mesh size to cope with MHI's wide variety of engines with cylinder sizes ranging from 70 to 960 mm. As an example, **Figure 3** shows a newly introduced model of the kinetic momentum transfer between liquid droplets and gas.[1]

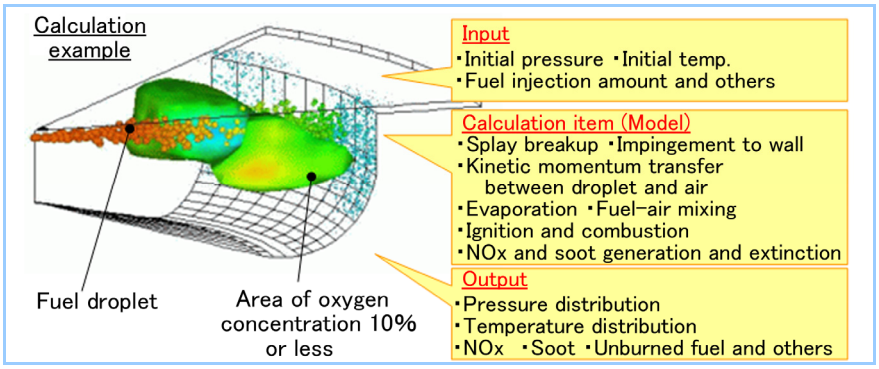

Figure 2 Outline of the combustion simulation

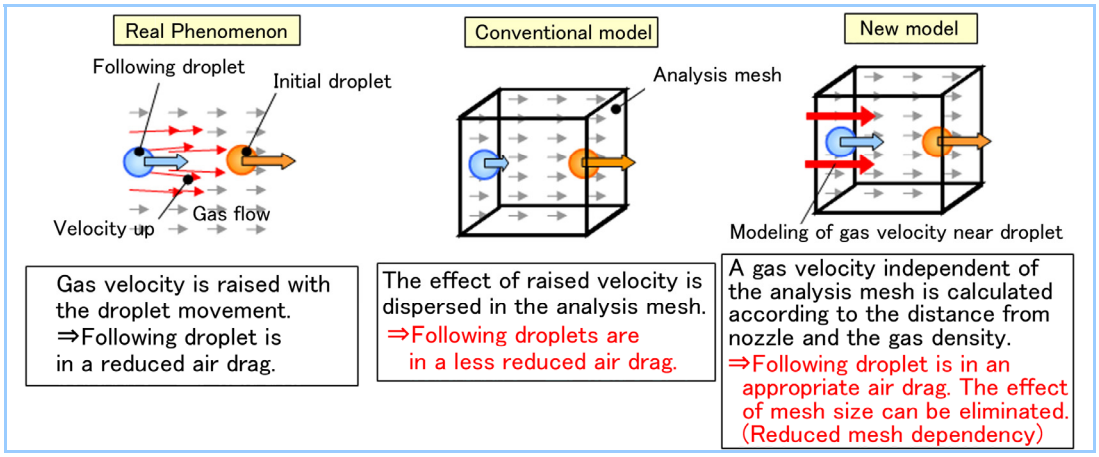

Figure 3 Kinetic momentum transfer between a droplet and the gas - reduced mesh dependency

3. Verification of Results

To verify the simulation results, we first calculated spray tip penetrations under non-reactive conditions and then the cylinder pressure and emissions under real engine conditions.

3.1 Spray tip penetrations under non-reactive conditions

We first compared the simulated and measured fuel spray movement in a non-reactive, high-temperature and high-pressure chamber filled with nitrogen gas. The distribution of the fuel spray determined the resulting flame distribution. Precise calculations of the spray penetrations are indispensable in predicting the cylinder pressure and emissions.[2] **Figure 4** compares the simulated and measured results, as summarized below.[3]

- In a conventional simulation, the mesh size had a large effect on the moment-to-moment spray location. A larger mesh size dispersed the gas velocity around a droplet and reduced the droplet velocity.
- In the newly developed model, the mesh size had little effect on the spray penetrations, and the calculated results were in good agreement with the measured values. This was because the momentum transfer between the liquid droplet and gas was modeled, reducing the dependence on mesh size.

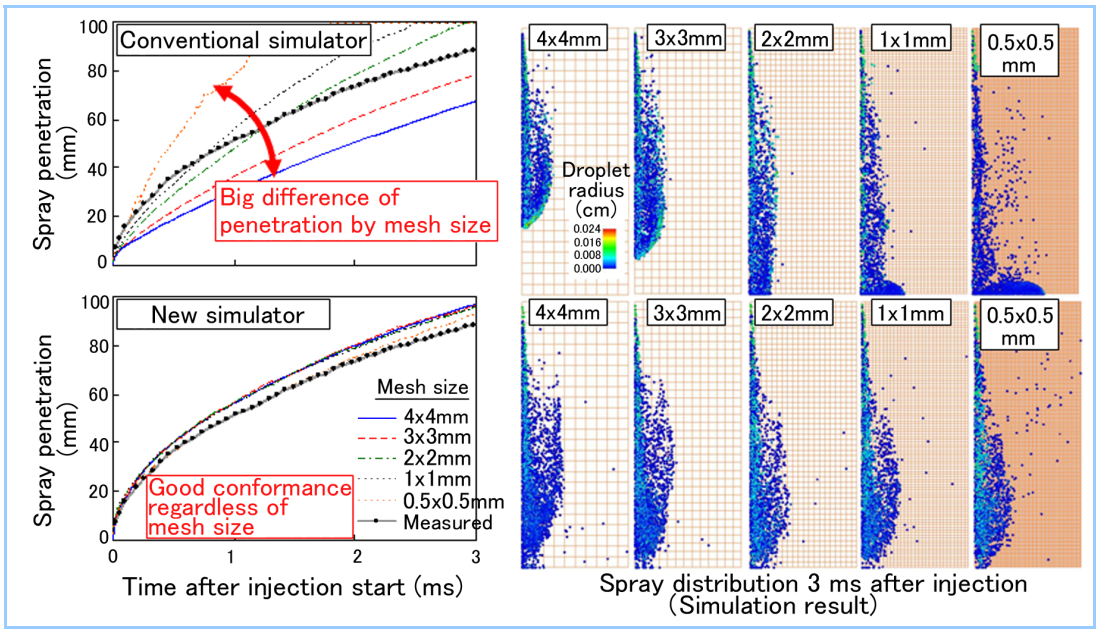

Figure 4 Spray penetration for different mesh sizes
Moment-to-moment location (left) and simulation results of the spray distribution after 3 ms (right). The latest model produces results that are in good agreement with the measured values, regardless of the mesh size.

3.2 Verification of the Calculated Cylinder Pressure and Emissions in a Real Engine

We next verified the simulations under actual engine conditions. Three engines were considered: a small agricultural engine (50-kW class), a mid-sized generator engine (8,000-kW class), and a large marine engine (30,000-kW class). **Figure 5** shows the measured and calculated cylinder pressure of each engine. The results are summarized below.

- The calculated values showed good conformance to the measured values, independent of the engine size. In particular, the small agricultural and mid-sized generator engine pressure predictions were in good agreement, including the absolute peak pressure value.
- For the large marine engine, although the calculations gave a lower pressure than the measured values by approximately 5%, the peak pressure timing conformed to the measured timing and the overall calculations seemed to be in good agreement with the measured values. The lower peak pressure was caused by the difference in construction between the small and mid-sized engines, and the large engine. The large engine had a fuel injector at the periphery of the combustion chamber while the smaller engines had the injector at the center of the chamber. This will affect the position and shape of the combustion flame.

Figure 6 compares the measured and calculated values of NO_x and soot emissions as the exhaust gas recirculation (EGR) rate (rate of exhaust gas supplied to the intake air to reduce NO_x) was changed. These results were also in good agreement, verifying that our model is useful for predicting emissions as well as the cylinder pressure. Also, the results of our model can be used as the boundary conditions for a finite element method (FEM) analysis for the engine construction to allow good predictions of the thermal stress and bearing temperature, which affect the engine reliability.

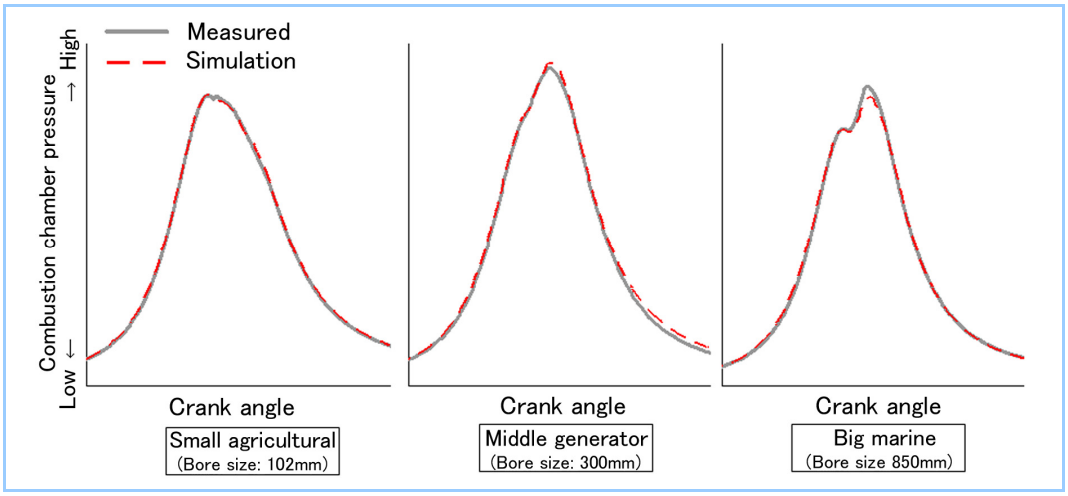

Figure 5 Measured and calculated cylinder pressures of the three types of engines

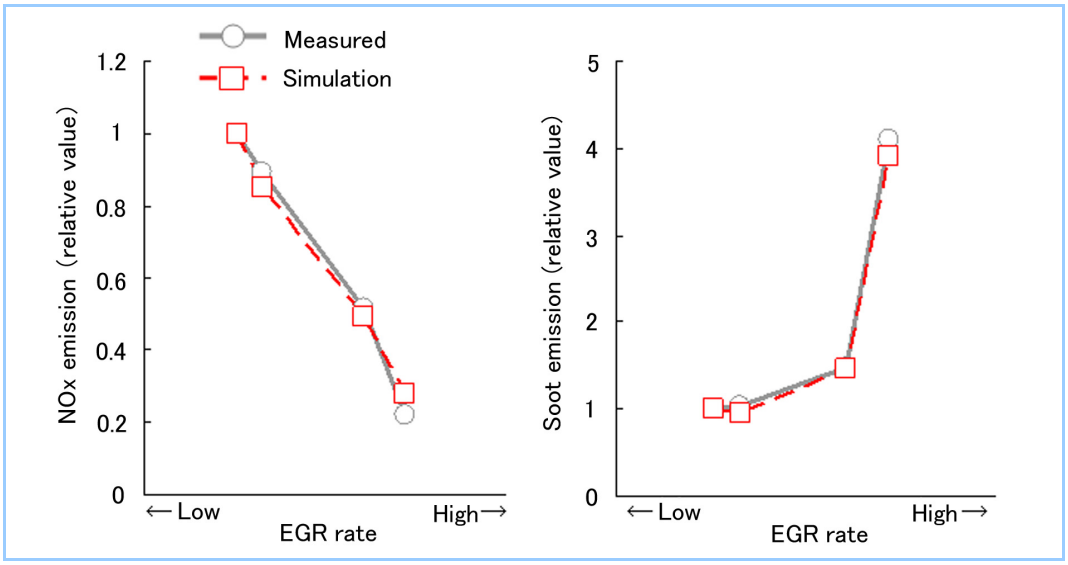

Figure 6 Verification of emission changes with the EGR rate
Calculations using the small agricultural engine. The NOx and soot results were in good agreement with the measured data.

4. Application to Engine Development

In this paragraph, we introduce an optimization method for the combustion chamber shape. This optimization can be conducted within a short period of time using our model. **Figure 7** shows the developed shape parameter optimization tool, which determines the combustion chamber shape by setting up the geometric parameters and utilizing an optimization tool based on the simulated annealing method. With this tool, an optimized combustion chamber shape that will reduce NO_x and soot emissions compared to the base shape can be calculated in approximately 50 hours (requiring 100 optimization searches), as shown in **Figure 8**.

In conventional optimization techniques, several shape parameters are selected, and the best shapes are determined after a conducting a test with an actual engine. Therefore, the optimum shape cannot necessarily be found within a reasonable number of tests. This method allows us to predict an optimized shape. Verification tests can then be performed along with some backup ideas to determine an optimized combustion chamber shape over a short time period.

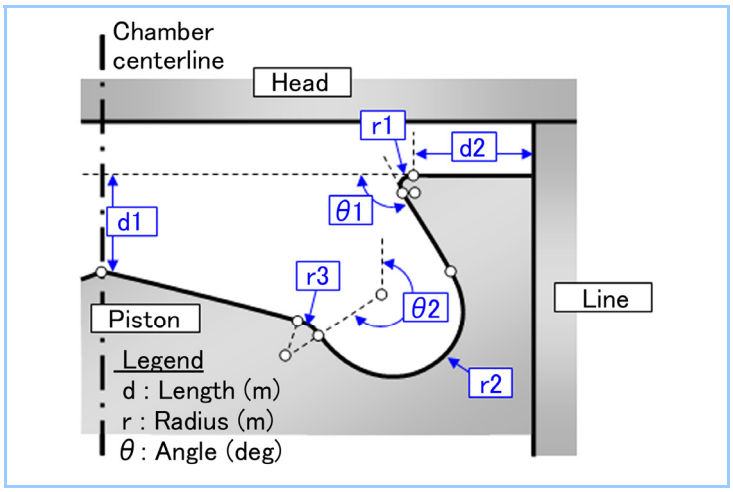

Figure 7 Combustion chamber parameters

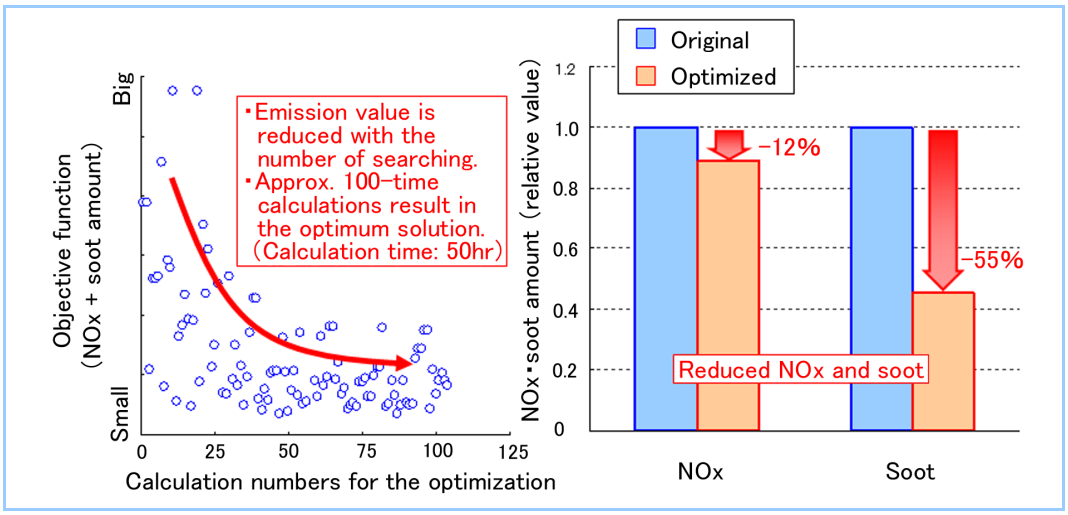

Figure 8 Optimization results for the combustion chamber

5. Conclusion

We have developed a simulation model that can calculate the conditions in a combustion chamber, and compared its predictions with values measured in actual engines. The results show that the cylinder pressure, which has a large effect on the fuel consumption, can be predicted accurately. Three MHI engines were considered in these tests: a small agricultural engine, a mid-sized generator, and a large marine engine. The model accurately predicted the heat stress and bearing temperatures, which are used in structural analyses. Also, the emission characteristics, including the amounts of NO_x and soot, can be predicted precisely in accordance with changes in the EGR rate. Optimization results were obtained in approximately 50 hours; these can be used to ensure rapid engine development by reducing the amount of testing required to determine the optimum shape for the combustion chamber.

References

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