Development of EPA Tier 4 Certified Diesel Engines for 2-3t Forklift Trucks

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For 2 to 3-ton class forklift trucks, Mitsubishi Heavy Industries, Ltd. (MHI) has developed the D04EG engine, which is in compliance with both the Japanese 2014 emission standards and the Tier 4 emission regulations of the U.S. Environmental Protection Agency (EPA). In the D04EG engine, the particulate matter (PM) levels emitted from the engine have been substantially reduced from those of existing models, and therefore it meets the latest emission regulations without using diesel particulate filters (DPF), keeping the cost low and realizing good usability for forklift truck drivers. For product development, we used our combustion simulation technology to newly design the shape of the combustion chamber and fuel injectors. Thus, we have simultaneously realized both reduced emission levels and lower fuel consumption.

1. Introduction

Because of their high-thermal efficiency and versatility, diesel engines are used as a power source for vehicles in various fields such as industrial, agricultural and construction machines. MHI has been developing diesel engines for industrial vehicles including forklift trucks, and have made them available commercially for our customers.

In recent years, the regulations on diesel engines have become particularly stringent in developed countries. For example, the U.S. EPA Tier 4 emission regulations on off-road engines, which have been effective since 2013, require PM emissions to be reduced to 1/10 of the previous level (**Figure 1**).

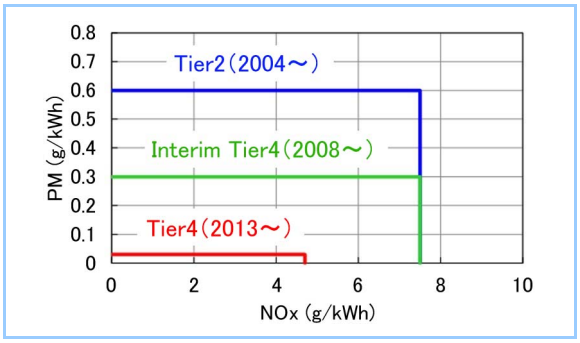

Figure 1 U.S. EPA emission regulations on off-road engines (19 to 37 kW)

With regard to exhaust emission measurement, as shown in **Figure 2**, the Non-Road Transient Cycle (NRTC) test has been introduced in addition to the conventional C1 steady test cycle. Therefore, it is also necessary to lower PM emissions during transient operation. Because of this enforcement of PM emission regulations, many Tier 4-certified engines employ DPF as a

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diesel exhaust after-treatment system. However, our D04EG engine for 2 to 3-ton forklift trucks does not require the use of DPF, yet successfully conforms to the Tier 4 regulations because of its minimized PM emission levels from the engine.

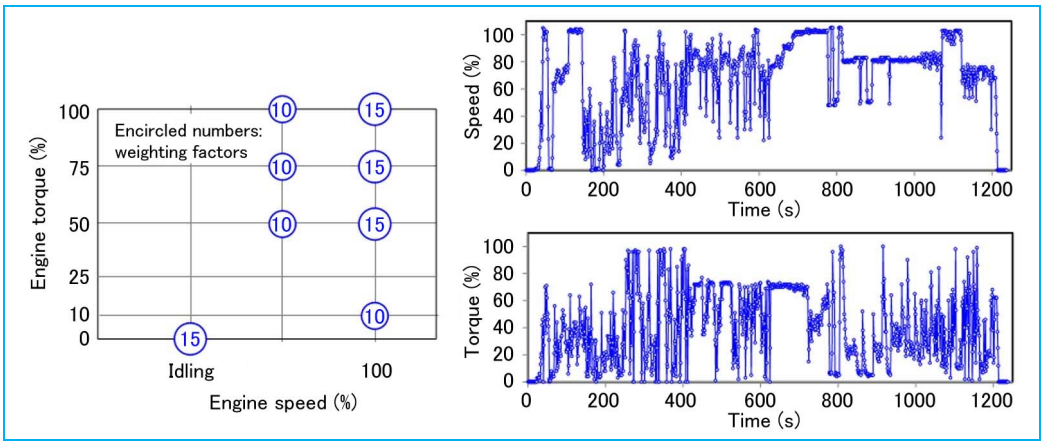
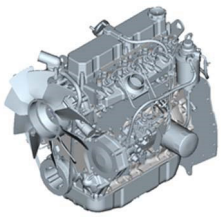
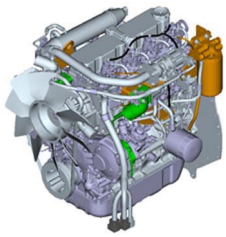


Figure 2 Steady-state C1 test cycle (left) and NRTC (right)

2. D04EG engine for 2 to 3-ton forklift trucks

Table 1 shows the specifications of the existing model (S4S engine) and the D04EG engine for forklift trucks. The S4S engine is well known for its high durability. While being based on it, the D04EG engine employs a common-rail fuel injection system and cooled external exhaust gas recirculation (EGR), both of which are electrically controlled. Their optimal control simultaneously realizes reductions in both exhaust emissions and fuel consumption. Considering the operational characteristics of forklift truck engines, we have determined that engine displacement should be 3.3 liters (which is relatively large as an engine for forklift trucks of the same class) combined with a naturally aspirated air intake system, thus securing high low-speed torque and superior engine response. As a diesel exhaust after-treatment system, only diesel oxidation catalysts (DOC) are used (i.e., there is no use of DPF) to decrease the concentration of soluble organic fraction (SOF) contained in PM. The fact that DPF is not used produces huge advantage in terms of cost, applicability and maintenance.

Table 1 Engine specifications

		Conventional model	Tier 4-certified model
Engine model		S4S	D04EG
Exterior view			
Bore×stroke	mm	94×120	94×120
Number of cylinders	—	4	4
Engine displacement	Liter	3.3	3.3
Rated output/engine speed		35.3/2250	36/2250
Maximum torque/engine speed		177/1700	177/1800
Fuel injection system	—	Mechanical pump	Electrically-controlled common rail
Air intake system	—	Natural aspiration	Natural aspiration
Exhaust gas recirculation	—	Nil	Cooled external EGR
Exhaust after-treatment system	—	Nil	Diesel oxidation catalyst

3. Use of combustion simulation to assess PM reduction measures

3.1 Measures for reduction of PM levels

In developing a product that conforms to the regulations without the use of DPF, there was the need to considerably reduce the PM level emitted from the engine. As PM mainly consists of

soot and SOF, our design first minimizes soot formation by improving combustion and then targets SOF-rich PM by DOC. In the combustion process of diesel engines, the formation of soot starts immediately after ignition at the center of fuel injection (i.e., low oxygen concentration area), and reaches its peak in the middle of the burning process. At the later stage of combustion, soot is mixed with air and is subject to re-combustion. The key issues for soot emission reduction are (1) the suppression of soot formation immediately after ignition by taking in large quantities of air in sprayed fuel before it ignites, and (2) the acceleration of soot re-combustion by facilitating mixing with air at the later stage of combustion. Therefore, as solutions to (1), the D04EG engine employs smaller diameters of injector nozzles and higher pressure of fuel injection. Likewise, the shape of the combustion chamber has been adjusted to achieve (2). **Figure 3** shows the relationship between the excess air ratios of sprayed fuel at ignition and soot emissions. As smaller diameters of injector nozzles and high-pressure injection can elevate the excess air ratio of sprayed fuel, the D04EG engine produces less soot. With regard to re-designing the combustion chamber shape, we used diesel combustion simulation (see the following section) to visualize the inside of the chamber, extract the possible shape for improvement, and determine the details of the design according to the simulation results.

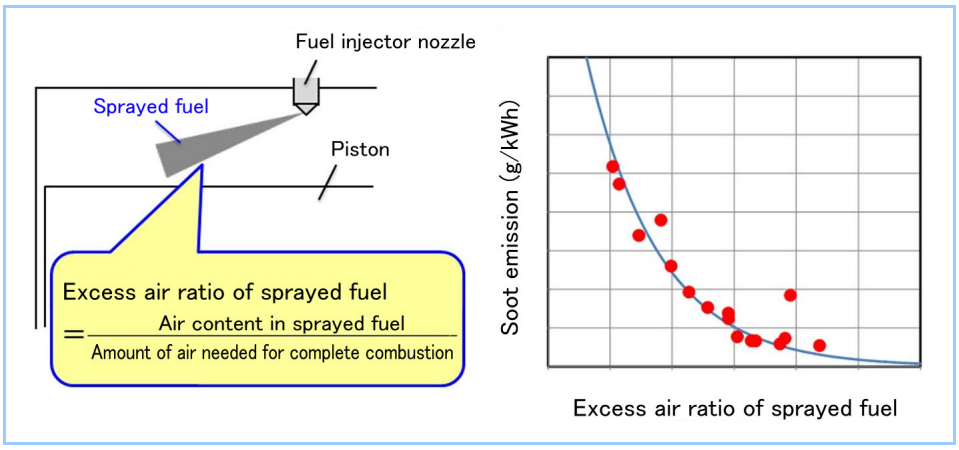


Figure 3 Relationship between excess air ratios of sprayed fuel and soot emissions

3.2 Diesel combustion simulation

In diesel combustion simulation, the computational fluid dynamics (CFD)-based models of a series of processes in the combustion chamber (including formation of fuel spray, evaporation, mixing, ignition, combustion, and exhaust gas production) are incorporated (**Figure 4**). The simulation can predict every moment of the changing processes that takes place in the combustion chamber, in terms of the distribution of temperature, pressure, fuel, exhaust gas, etc. The behavior of injected fuel spray and consequent chemical reactions can greatly affect how combustion occurs. Their models have been developed in cooperation with the University of Wisconsin in the U.S., which is known for its abundant component-test data and excellent modeling technology.

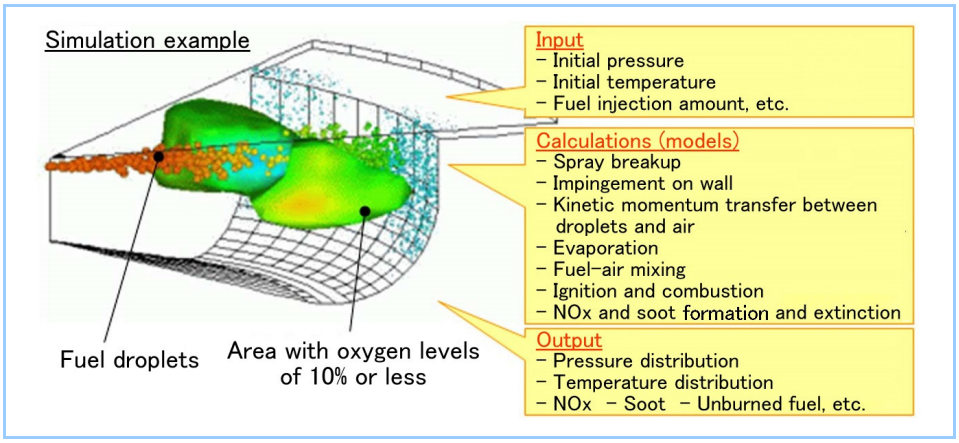


Figure 4 Outline of combustion simulation

Figure 5 shows an example of simulation results regarding NOx and soot emissions against EGR rate. These are in good agreement with the measurement results obtained under the real engine conditions, which therefore verifies the reasonableness of using the simulation to examine the effect of newly-contrived emission reduction measures before building prototypes. As this can minimize the possibility of redoing the work after the completion of prototypes and can cut down on the number of experiments to be carried out, the product development period can shortened considerably. Although it is difficult to actually see what is happening inside the combustion chamber during combustion, we can visualize it using the simulation and discuss the options for improvement in more detail.

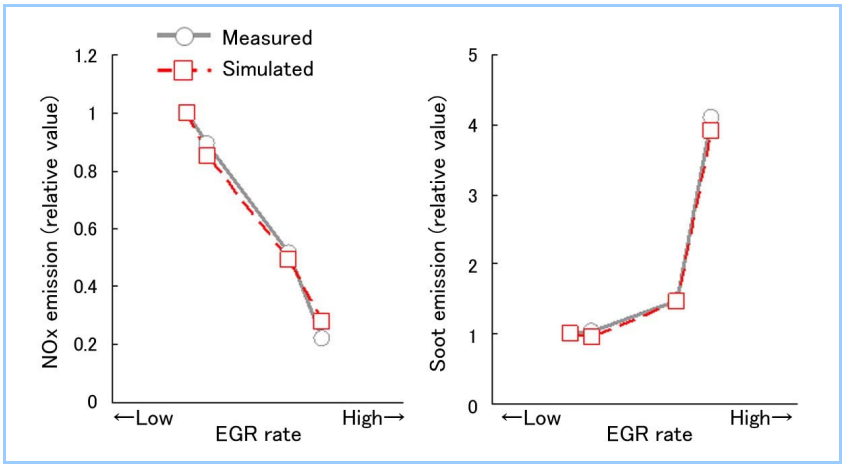


Figure 5 Verification results of combustion simulation accuracy regarding gas emissions

3.3 Determination of the shape of combustion chamber using combustion simulation

In order to lower the soot concentration in PM, we reconsidered the shape of the combustion chamber using combustion simulation. Our goal is to facilitate soot re-combustion by producing more uniform dispersion of sprayed fuel after it collides with the wall of the combustion chamber and making better use of the air in the combustion chamber.

We simulated the combustion process with and without a change in the shape of the combustion chamber. **Figure 6** shows the visualization results on the behavior of sprayed fuel. After being injected, fuel spray reaches the combustion chamber wall at the crank angle of 4 degrees, followed by upward and downward dispersion along the wall. While the results of the conventional chamber shape show that most of the dispersed fuel stays at the lower part of the chamber, the upward/downward distribution of dispersed fuel becomes relatively uniform along the wall when the improved shape is applied.

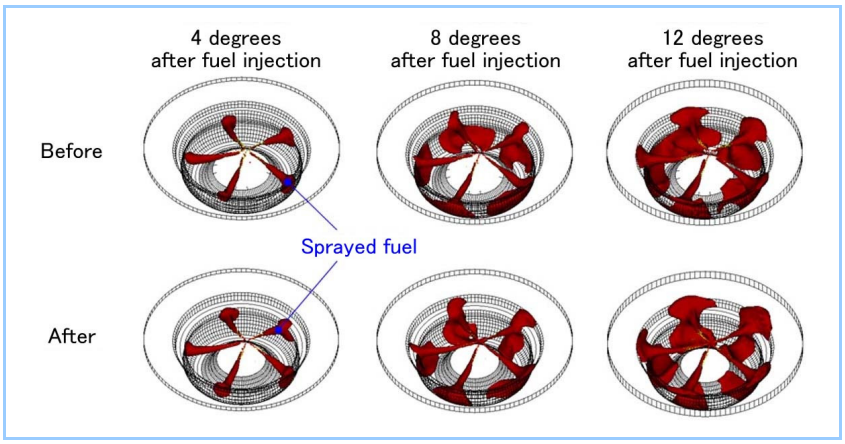


Figure 6 Visualization results on the behavior of sprayed fuel using combustion simulation

Soot distribution during combustion was also simulated under the same conditions as Figure 6. The visualization results are given in **Figure 7**. At the crank angle of 12 degrees after fuel injection, the presence of soot is largely seen in the piston cavity in either case of with or without a change of chamber shape. However, at the crank angle of 22 degrees after injection, the conventional shape shows that most of the soot remains in the cavity. On the other hand, with the improved shape, soot is also present at the upper part of the chamber, indicating the improved use of the air throughout the chamber. As a result, most of the soot is burned down at the crank angle of 32 degrees after injection, which makes a clear contrast to the conventional shape, which has a copious amount of soot still remaining in the cavity. Thus, the simulation results show that, with the improved chamber shape, soot re-combustion is facilitated as intended.

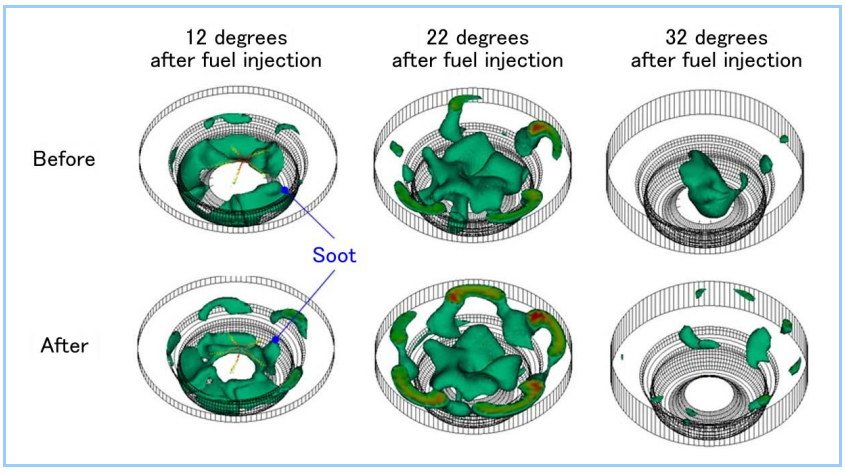


Figure 7 Visualization results of soot distribution using combustion simulation

3.4 Test results of engine performance demonstration

Figure 8 shows the results of performance verification testing using actual test engines with or without the improved shape of the combustion chamber. As expected, the improved shape substantially reduced soot emissions from those of the conventional shape. When the timing of fuel injection was advanced, soot emissions increased in the conventional shape, whereas there was no such rise in the improved shape. We owe this result to our use of combustion simulation, which enabled us to design a combustion chamber with a robust shape despite the timing of fuel injection. For the realization of better fuel efficiency, it is an effective measure to advance the timing of fuel injection. Therefore, the use of the combustion chamber with the improved shape allows the injection timing to be advanced without elevating soot emissions, leading to improved fuel efficiency.

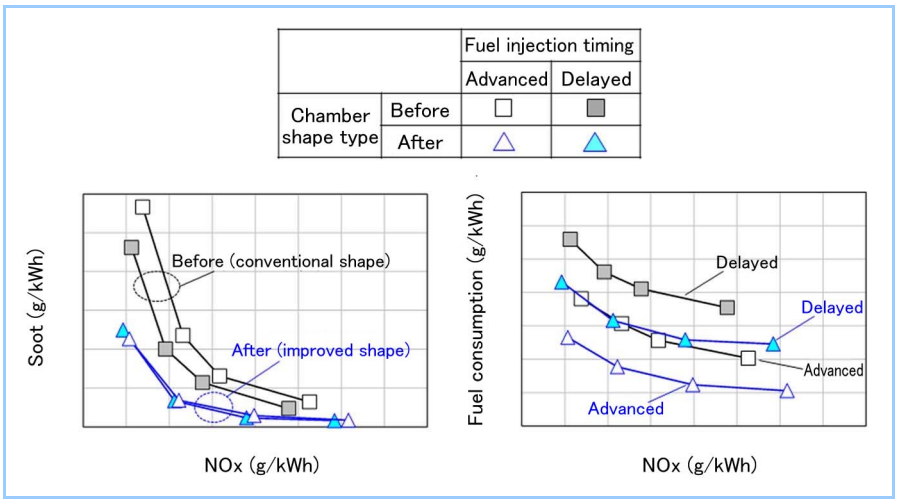


Figure 8 Verification results of performance improvement effect with the change in the combustion chamber shape

Figure 9 compares the engine performance results between the D04EG and the existing model. The D04EG engine has made considerable improvement in both fuel efficiency and PM emissions compared with the existing model. In exhaust emission measurement, the obtained values fell below the prescribed limits in the C1 steady test and NRTC test, thus verifying compliance with the Tier 4 emission regulations. It has also been demonstrated that forklift trucks with the D04EG engine can reduce fuel consumption by approximately 20% compared with the existing model (according to the measurement pattern by the customer). Therefore, the D04EG engine not only conforms to the latest emission regulations, but also possesses superior fuel efficiency.

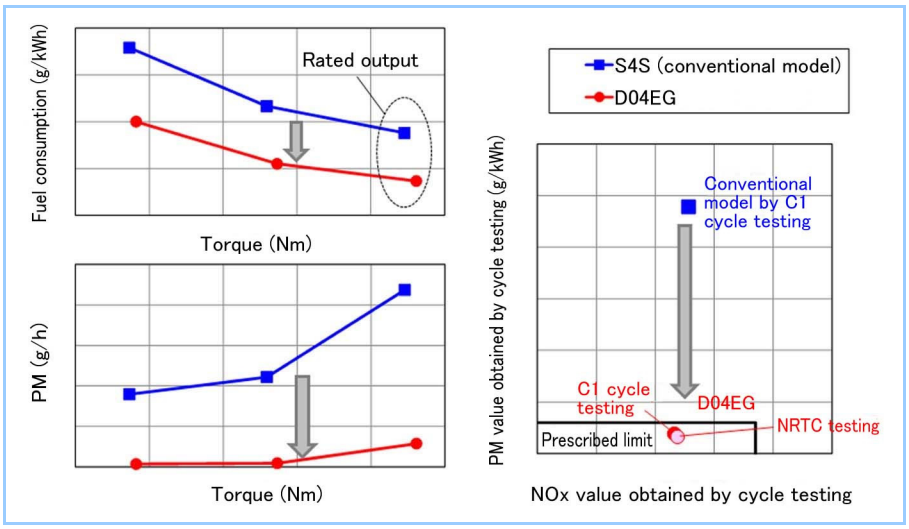


Figure 9 Test results of engine performance demonstration

4. Conclusion

We have developed the D04EG engine for 2 to 3-ton class forklift trucks, which is in compliance with both the U.S. EPA Tier 4 emission regulations and the Japanese 2014 emission standards. To satisfy the latest emission regulations without using DPF, PM levels emitted from the engine had to be substantially reduced from those of the existing model. However, using our combustion simulation technology for re-designing the combustion chamber and fuel injectors, we have realized engine performance that meets the emission regulations.

The D04EG has already obtained emission certification and has been commercially manufactured since 2014. We will continue to develop engines that are worthwhile to our customers through the utilization of our component technologies.

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