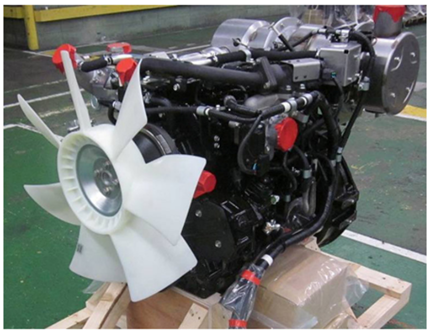
Development of EPA Interim Tier 4 Certified Small Diesel Engine



KENJI HIRAOKA[*1] SATOSHI YAMADA[*1]
KAZUNARI IDE[*2] KAZUKI NISHIZAWA[*3]
TOMOHIDE YAMADA[*4] AKIHIDE OKAJIMA[*5]

Diesel engines are used as a power source for various industrial machines because they have greater fuel versatility and are more fuel efficient than other internal combustion engines. Meanwhile, emission regulations have been tightened year after year. In the United States, the EPA Interim Tier 4 emission regulations for engines with a rated output of 56 kW or more to less than 75 kW become effective in 2012. To meet these regulations, a further reduction of emissions is required. The particulate matter (PM) emission amount, for example, needs to be reduced to 1/20 compared with the required level of the conventional regulations. MHI has developed the D04EG engine in compliance with the EPA Interim Tier 4 emission regulations, which reduce the regulated substances further than engines certified the conventional regulations, while also attaining higher fuel efficiency.

1. Introduction

Diesel engines are used as a power source for various industrial machines such as construction and agricultural machinery because they have great fuel versatility and are fuel efficient. In the past, MHI developed and commercialized engines in compliance with the Tier 3 emission regulations to offer customers high-performance and high-reliability engines.

Meanwhile, emission regulations enforced mainly in Japan, Europe, and the United States have been tightened year after year. **Figure 1** shows the trend of emission regulations for off-road engines established by the U.S. EPA.

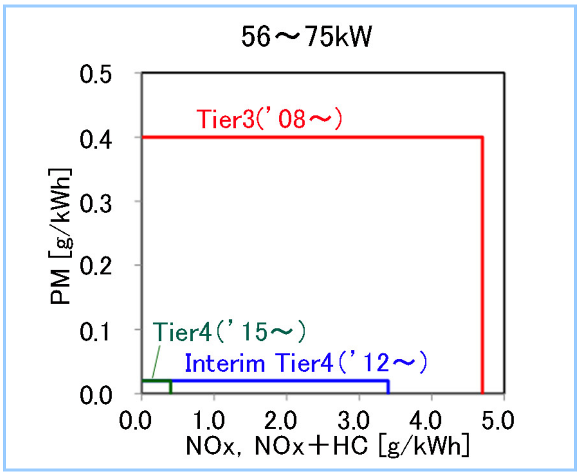


Figure 1 U.S. EPA emission regulations for off-road engines (56 to 75 kW)
The horizontal axis represents NOx+HC for Tier 3, and NOx for Tier 4 and later.

For engines with a rated output of 56 kW or more to less than 75 kW, the EPA Interim Tier 4 emission regulations that become effective in 2012 in the United States require the further reduction of emissions. The PM emission amount, for example, needs to be reduced to 1/20

*1 Yokohama Resarch & Development Center, Technology & Innovation Headquarters
*2 Manager, Nagasaki Research & Development Center, Technology & Innovation Headquarters
*3 Chief Staff Manager, Yokohama Resarch & Development Center, Technology & Innovation Headquarters
*4 Senior Engineer, Engine Engineering Department, Engine Division, General Machinery & Special Vehicles
*5 Manager, Engine Engineering Department, Engine Division, General Machinery & Special Vehicles

compared with the required level of the conventional Tier 3 regulations. In addition, the EPA Interim Tier 4 emission regulations newly employ NRTC (non road transient cycle) test, and therefore require emission evaluation during not only steady operation, but also transient operation (**Figure 2**).

To respond to these regulations, MHI has created combustion chamber shape adjustment technology, fuel injection control technology with CRS (electronic controlled common rail system), EGR (exhaust gas recirculation) control technology for transient operation, and emission after-treatment system control technology, and combined them to develop the D04EG engine in compliance with the EPA Interim Tier 4 emission regulations, which reduce the regulated substances further than engines meeting the conventional regulations, while also attaining higher fuel efficiency.

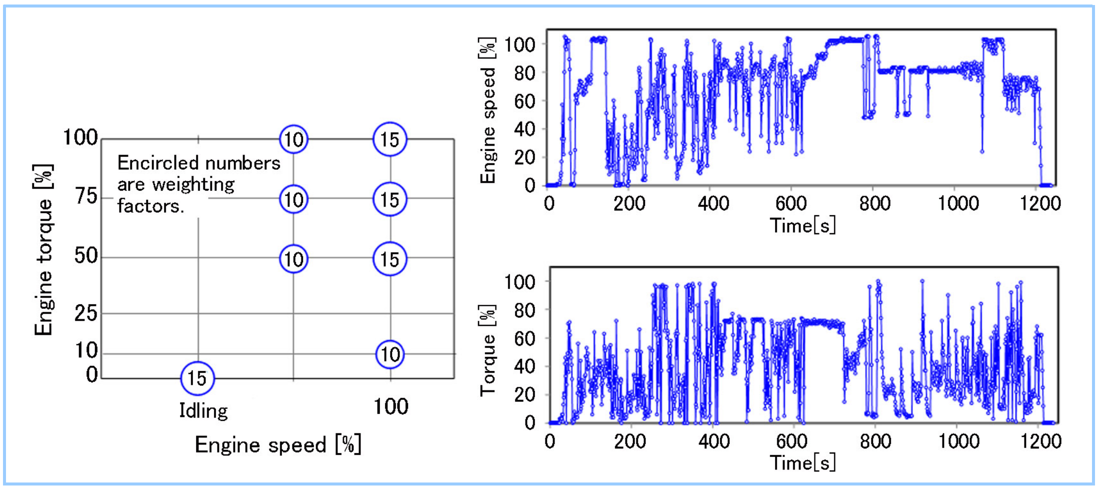


Figure 2 C1 steady test (left) and NRTC test (right)

2. D04EG engine specifications

Table 1 shows the specifications of the newly developed D04EG small diesel engine and conventional D04FR engine. The output per engine displacement of the D04EG has been enhanced to attain lower fuel consumption than a conventional engine. **Figure 3** compares the output and fuel consumption between the newly developed and conventional engines. The newly developed engine attains an approximately 5 to 8% reduction of fuel consumption compared with a conventional engine by lowering friction loss through downsizing of the engine and other methods. In addition, the D04EG utilizes an external EGR system and emission after-treatment system for the reduction of emissions over the entire operating range of the engine.

Table 1 Specifications of engine certified Tier 3 regulations (D04FR) and engine certified Interim Tier 4 regulations (D04EG)

		Certified Tier 3	Certified Interim Tier 4
Engine model		D04FR	D04EG
Bore x stroke	mm	102×130	94×120
Number of cylinders		4	4
Engine displacement	Liters	4.2	3.3
Rated output / engine speed	kW/rpm	74/2000	74/2000
Maximum torque / engine speed	N・m/rpm	375/1600	375/1600
Fuel injection		Common rail	Common rail
Turbocharger		Turbocharger	WG turbocharger
Exhaust gas recirculation		Internal EGR	External EGR
Dimensions L×W×H (*1)	mm	911×719×940	879×689×848
Weight	kg	Approximately 410	Approximately 360

*1 Sole engine dimensions excluding after-treatment system

Although the new devices shown above have been added, the newly developed engine maintains dimensions equivalent to those of a conventional engine due to the downsizing of the engine itself (**Figure 4**), and therefore any required change of the space for mounting the engine on a vehicle is minimized.

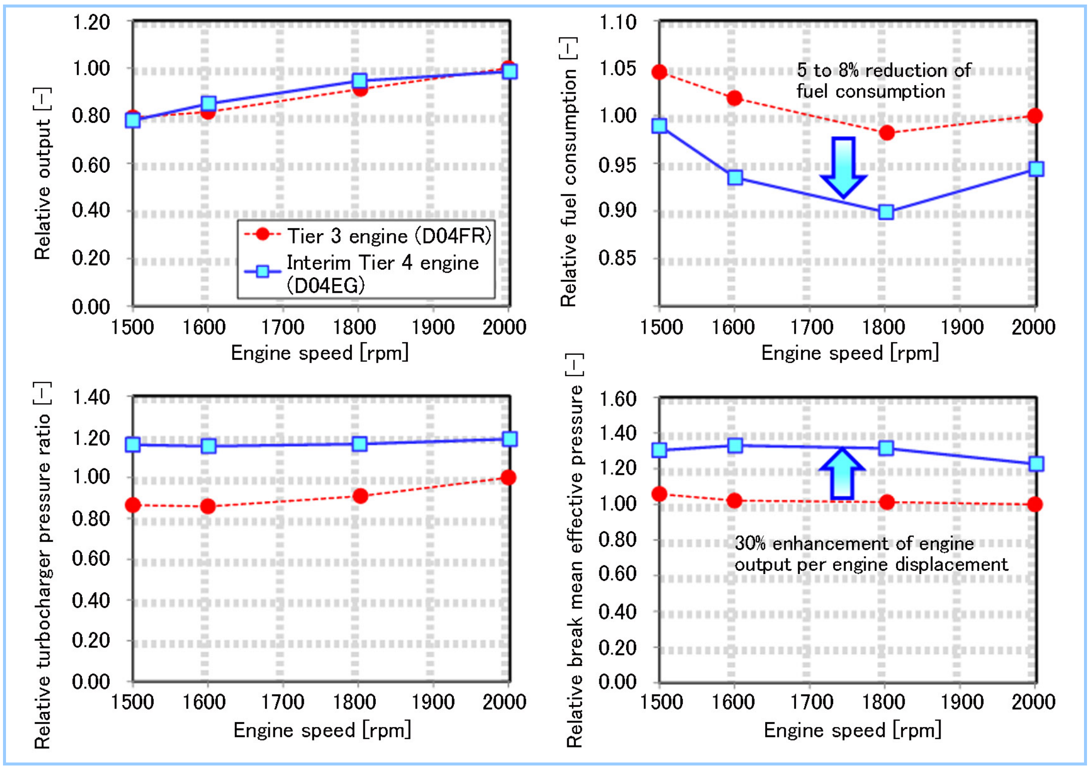


Figure 3 Comparison of engine performance between engine certified Tier 3 regulations (D04FR) and engine certified Interim Tier 4 regulations (D04EG)

Each item represents the relative value assuming that the value obtained with the D04FR at an engine speed of 2000 rpm is 1.00.

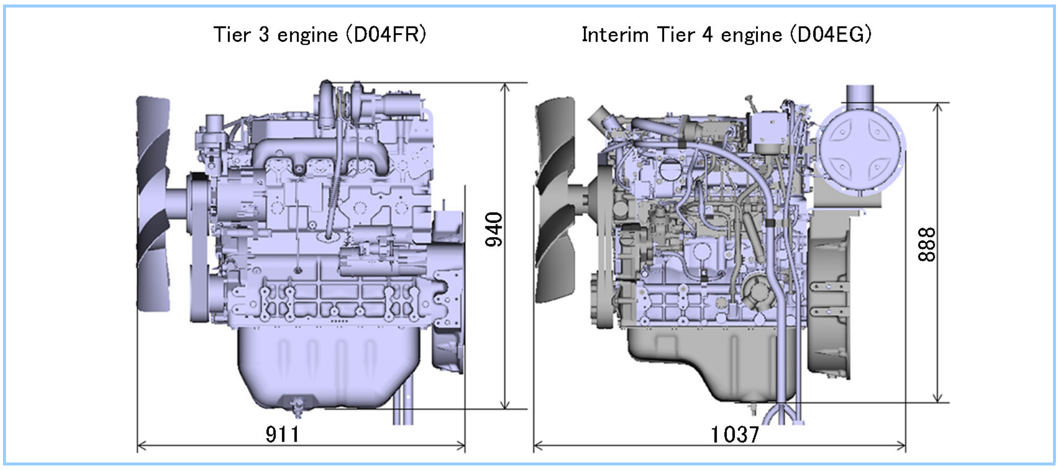


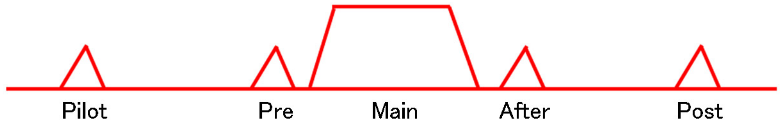
Figure 4 Comparison of engine dimensions between engine certified Tier 3 regulations (D04FR) and engine certified Interim Tier 4 regulations (D04EG)

3. Technology for reduction of emissions

As emission reduction measures, the newly developed engine uses CRS and EGR, adjusts the shape of the combustion chamber, and features a DPF (diesel particulate filter (PM trap device)) for the trap and reduction of PM emitted by the engine. MHI used numerical simulation and optimization methods to work on the technological development efficiently in order to select and determine the specifications, operating conditions, and control methods of the emission reduction measures. This section describes the details.

3.1 Fast adjustment of fuel injection pattern utilizing optimization methods

The employment of CRS and an external EGR system has made possible the fine control of the fuel injection pattern and oxygen concentration in the intake air in response to engine operating conditions. CRS can arbitrarily control the number of injections, injection timing, and injection amount (**Figure 5**). External EGR can arbitrarily adjust the oxygen concentration in the intake air by controlling the opening of the EGR valve. However, there are as many as hundreds of millions of combinations, and the optimization of the injection pattern over the entire operating range can be time-consuming.



	Pilot	Pre	Main	After	Post
NOx	↓	↓	-	↓	-
HC	↑	−	-	↓	↑
CO	↑	↑	-	↓	-
PM	↑	↑	-	↓	-
Fuel consumption	↑	↓	-	↑	↑
Noise	↑	↓	-	↓	-
Main application	NOx reduction	Noise reduction	Output control	PM reduction	DPF regeneration

↓: Decrease, improvement
↑: Increase, worsening

Figure 5 Fuel injection patterns and their effects

Therefore MHI utilizes optimization supporting tools to efficiently adjust multiple control parameters in a short time. The use of a hybrid optimization method that combines an orthogonal table test, a response surface model and an optimization method has made possible the selection of the most appropriate control parameters in a short time in response to operating conditions.

3.2 Employment and control technology of EGR (exhaust gas recirculation system)

The D04EG newly employs an external EGR system to reduce NOx (nitrogen oxide) formation in the combustion chambers. EGR returns some of the exhaust gas to the intake to reduce the oxygen concentration in the combustion chambers. This lowers the combustion temperature, and consequently NOx formation can be suppressed.

For the efficient reduction of NOx formation through EGR, it is necessary to introduce EGR gas into each cylinder evenly. To attain this, variation of the amount of EGR gas introduced between cylinders is controlled by using numerical simulation and adjusting the shape of the EGR introductory part (**Figure 6**).

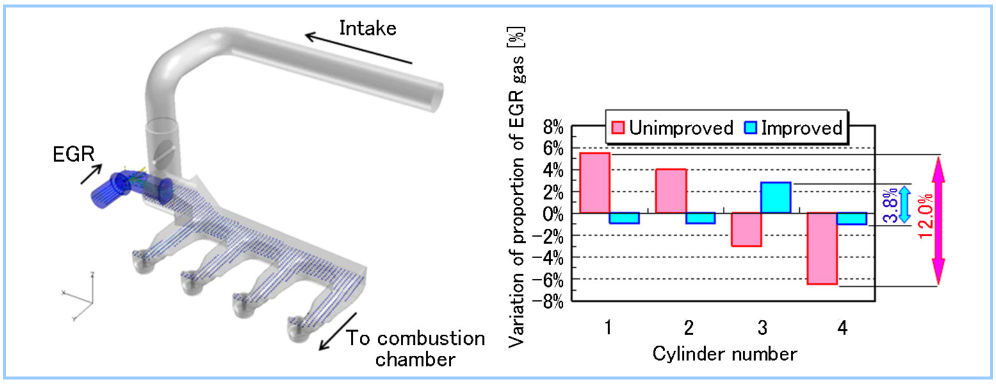


Figure 6 Numerical simulation results for improvement of introductory part of EGR

Under operating conditions where the engine load changes transiently, such as the NRTC transient evaluation mode newly added for the EPA Interim Tier 4 emission regulations, the amount of air in the combustion chamber becomes insufficient because of a delay in the response of the turbocharger or other factors, and then the PM emission amount increases. In addition, because the pressure difference between the intake and exhaust changes, the EGR introduction amount can also change.

Therefore appropriate EGR introduction control in consideration of the delay in the response of the turbocharger or other factors is required. The D04EG utilizes a control logic that uses an AFM (air flow meter) installed upstream of the compressor (turbocharger) for successive detection of air flow and pressure, as well as temperature sensors at the intake manifold to momentarily estimate excess air ratio (the ratio of actual air supply to the theoretical amount of air needed for combustion). This can significantly suppress the increase of the PM emission amount by feedback-controlling the EGR flow, so that the target excess air ratio is reached even in transient operation. **Figure 7** compares the results of a test on actual equipment between engines using the conventional open loop control and the newly employed feedback control. These results indicate that the feedback control can reduce the PM emission amount under conditions of actual use.

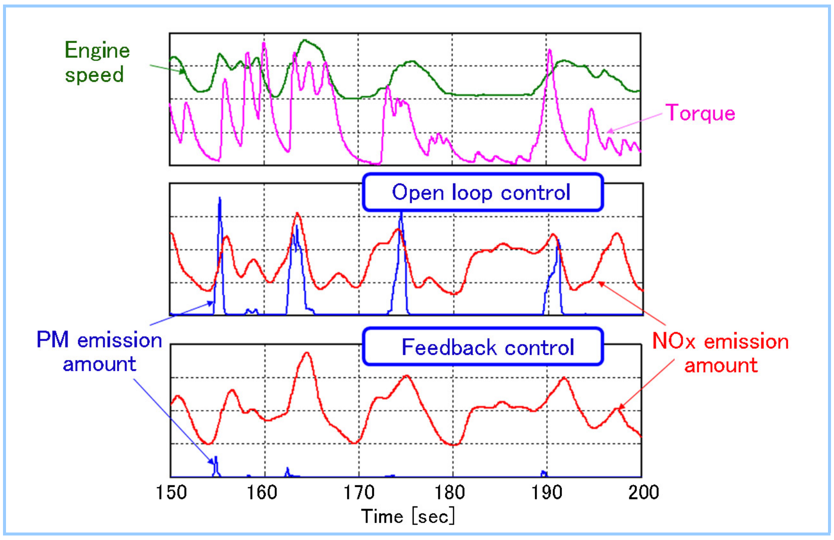


Figure 7 Reduction of PM due to feedback control
The feedback control can reduce the PM emission amount.

3.3 Combustion chamber shape adjustment through numerical simulation

The combustion chamber shape has been reviewed in order to reduce PM formation in the combustion chambers. In the past, several types of combustion chamber shapes were determined based on previous test data, and then the best shape among them was selected through tests on actual equipment. Because of the limited development period, however, the most appropriate shape could not always be found. This time, optimization technology of the combustion chamber shape with numerical simulation has been used, and then a combustion chamber shape that can further reduce the PM emission amount could be determined earlier compared with the conventional method. **Figure 8** shows the numerical simulation results of the combustion chamber employed this time. The combustion chamber shape and the fuel diffusion direction are optimized so that fuel injected by the injector is widely distributed in the combustion chamber. As a result, the air in entire combustion chamber can be used effectively, and therefore the PM emission amount can be reduced.

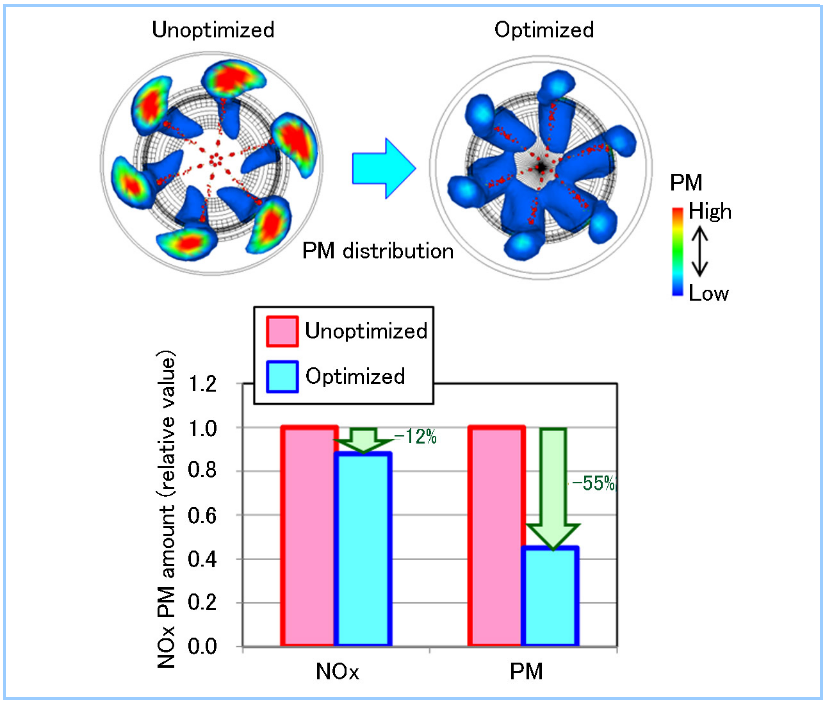


Figure 8 Results of combustion chamber shape adjustment with numerical simulation

3.4 Emission after-treatment system and its control technology

The D04EG employs DPF to reduce the PM emission amount. **Figure 9** illustrates an overview of the emission after-treatment system of this engine. DPF taps PM emitted from the engine with a filter. As a result, the PM emission amount of the entire engine system can be reduced. When the temperature of the emissions is higher than a certain value, PM trapped by DPF is regenerated continuously. However, if the engine is operated under conditions where the exhaust gas temperature is lower, PM accumulates in DPF, thus DPF regeneration that periodically burns and removes the accumulated PM is required.

MHI has established technology that can accurately estimate the PM accumulation in DPF, determine the timing of starting regeneration, and control the regeneration to prevent abnormal PM combustion causing burning of DPF or unburnt PM. PM can be burnt by introducing high-temperature emissions into DPF. The D04EG features a control system that raises the gas temperature at the DPF inlet to approximately 600°C by implementing post-injection (fuel injection during an exhaust stroke of the engine) in the combustion chambers, and allows unburnt fuel to react with DOC (diesel oxidation catalyst).

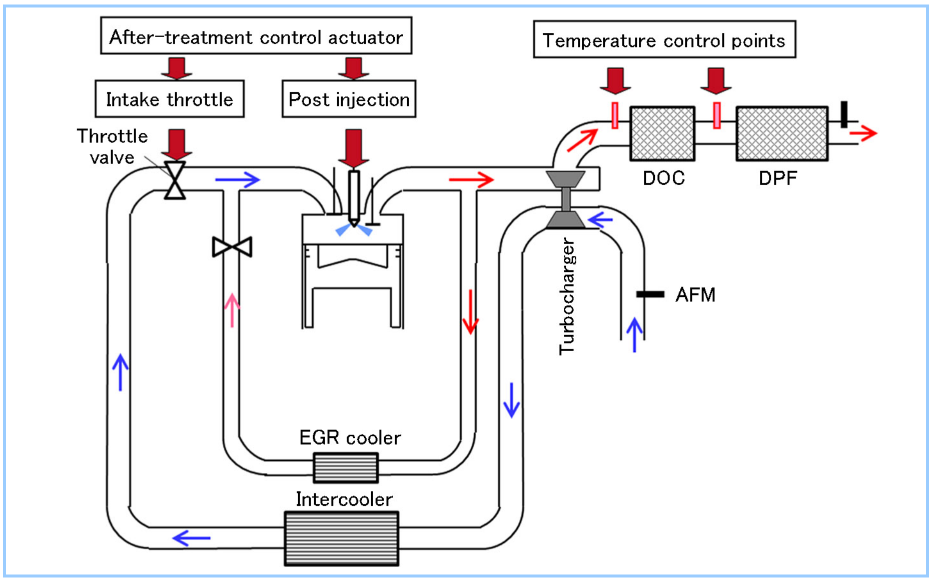


Figure 9 Control system structure of emission after-treatment system

4. Conclusion

MHI has developed the D04EG small diesel engine in compliance with the EPA Interim Tier 4 emission regulations, which reduce emissions further than conventional engines, while also attaining lower fuel consumption. In the development of this engine, MHI was able to efficiently optimize design and control parameters such as the combustion chamber shape and the fuel injection pattern through utilizing not only emission reduction technologies including EGR and DPF, but also numerical simulation and optimization technology.

The D04EG has already acquired EPA Interim Tier 4 and EU stage3b certifications, and its commercial production began in April 2012. It has also been verified on actual equipment that this engine can be in compliance with the EPA Tier 4 emission regulations (which will become effective in 2015) through the use of large-scale EGR, a variable flow turbocharger, and SCR (selective catalyst reduction) denitration technology.

References

1. Takai et al., Tier3 Emission Certified Small Engines, Mitsubishi Juko Giho Vol. 46 No. 1 (2009) pp. 40-42
2. Satake et al., The Rapid Development of Diesel Engines Using an Optimization of the Fuel Injection Control, Mitsubishi Heavy Industries Technical Review Vol. 45 No. 3 (2008) pp. 6-9
3. Yamada et al., Development of a Calibration Method for Optimum Operating Parameters of Diesel Engines, Trans. of JSAE Vol.39 No.6 (2008) pp. 131-135
4. Imamori et al., Combustion Simulations Contributing to the Development of Reliable Low-Emission Diesel Engines, Mitsubishi Heavy Industries Technical Review Vol. 48 No. 1 (2011) pp. 72-76
5. Hiraoka et al., The optimization method of DI engine parameters by KIVA, Trans. of JSAE Vol. 41 No. 1 (2010) pp. 97-102