Development of Diesel Engines for 2.0t to 3.5t and 3.5t to 5.5t Forklift Trucks Complying with EU Stage V Emission Standards

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For the development of D04EG engines, which comply with the European Stage V Non-Road Emission Standards (EU Stage V emission standards), we improved the combustion and developed a newly required DPF (diesel particulate filter) control. In order to produce a DPF control that meets market demands and evaluate the soot accumulation on the DPF, we acquired the actual operation data of multiple engines available in the market and created an evaluation index based thereon. We conducted verification with the created evaluation index and confirmed that reducing soot can significantly lower the frequency of DPF regeneration and that DPF regeneration can be completed during vehicle operation without interrupting work. We also conducted a field test and confirmed that the desired functions were realized with actual vehicles in the market.

1. Introduction

Mitsubishi Heavy Industries Engine & Turbocharger, Ltd. has developed and commercialized engines that comply with the North American Tier 4 standards and we have provided customers with engines featuring excellent performance, reliability and low emission[(1)].

This time we have developed the D04EG engine, which complies with the EU Stage V emission standards. The EU Stage V emission standards newly regulate the number of solid particulates (PN: particulate number) in exhaust gas, in addition to the reduction of emissions by the conventional exhaust gas regulations. To comply with the PN regulations, a DPF is practically indispensable and therefore DPF regeneration control for burning the soot accumulated in the DPF due to engine operation is required. Depending on the DPF regeneration control method, it is necessary to interrupt the work in order to perform DPF regeneration. For this reason, the realization of a DPF regeneration control that functions appropriately during normal engine operation plays an important role in making the engine more convenient.

2. Engine specifications

Table 1 lists the specifications of the engines that comply with the EU Stage V emission standards. We have newly developed two engine models by adding the DPF required to be in compliance with the EU Stage V emission standards to engines that meet the North American Tier 4 standards. In order to improve the combustion to comply with the EU Stage V emission standards, as well as to make it possible for the newly required DPF to be regenerated under any engine operating condition including lower speed and lower load, the new engine adopts an exhaust throttle valve. While complying with the EU Stage V emission standards, the developed engine minimizes the effects of the DPF installation on the vehicle by allowing the DPF to be installed

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away from the engine, and is configured by adding only a DPF and an exhaust throttle valve required for DPF regeneration to the North American- and Japanese-specification engines that do not require a DPF.

We have developed cleaner and more convenient engines by realizing a DPF regeneration control with high flexibility in addition to complying with exhaust gas regulations. This report presents the developed engine.

Table 1 Engine main specifications

Engine model name		4EG-NA	4EG-T
Bore x Stroke	mm	94×120	94×120
Number of cylinders	—	4	4
Displacement	Liter	3.3	3.3
Rated output/ speed	kW/min^{-1}	36/2250	54/2250
Maximum torque/ speed	$N \cdot m/min^{-1}$	177/1800	260/1800
Fuel injection system	—	Electronically controlled common rail system	Electronically controlled common rail system
Aspiration method	—	Naturally aspirated	WG supercharged
Exhaust gas recirculation	—	Externally cooled EGR	Externally cooled EGR
Exhaust gas aftertreatment device	—	Diesel particulate filter	Diesel particulate filter
Remarks		The following changes were made to comply with the EU Stage V emission standards from the engine models that meet the North American Tier 4 standards. - Change of the exhaust gas aftertreatment device to a diesel particulate filter (DPF). - New adoption of an exhaust throttle valve for DPF regeneration.	

3. Technologies for complying with EU Stage V emission standards

To be in compliance with the EU Stage V emission standards, a DPF is required in order to meet the PN regulations. The soot collected inside the DPF needs to be burned off (DPF regeneration) when a certain amount accumulates and it is desirable to reduce the frequency of DPF regeneration. Therefore, we worked on the reduction of soot emission from the engine and at the same time, made it possible to regenerate the DPF under any conditions during engine operation to realize a control that does not require the interruption of work in order to perform DPF regeneration.

3.1 Reduction of soot emission for reduction of DPF regeneration frequency

In order to reduce the frequency of DPF regeneration, it is necessary to reduce the particulate accumulation speed and the most effective measure is to suppress the generation of soot in the combustion chamber, which accounts for most of the particulates. In the combustion process of a diesel engine, soot starts to be generated in a low oxygen concentration region at the center of the fuel injection immediately after ignition, reaches a peak during combustion and then mixes with air in the latter half of oxidization, which leads to re-oxidization. Therefore, key points for reducing soot emission are to take in a large amount of air during fuel injection before ignition to suppress soot oxidization immediately after ignition and to promote mixing in the latter half of combustion to accelerate soot re-oxidization. This time, we achieved these goals by increasing the number of the injector nozzle holes and reducing their diameter and by improving the shape of the combustion chamber. This was done by using combustion simulation. The development was carried out while determining the specifications through theoretical investigation using the simulation and then confirming them through tests. **Figure 1** (a) presents the simulation results of improving the shape of the combustion chamber. It is indicated that, before the shape improvement of the combustion chamber, the fuel is distributed unevenly therein and after the improvement, on the other hand, it is distributed throughout the combustion chamber and mixes well. Figure 1 (b) gives the confirmation results obtained by an engine test using a combustion chamber with a shape determined by this simulation. It was confirmed that the soot was significantly reduced.

In order to reduce the frequency of DPF regeneration in the actual market, it is necessary to reduce soot emission in consideration of the transient behavior of the operating patterns used in the market. In this development, we carried out evaluations using multiple operating patterns prepared in advance. **Figure 2** is an example of the evaluation pattern. It is indicated that the soot emission was reduced significantly by the improvement. As a result, the DPF regeneration interval in a normal usage environment was extended to more than twice that of the conventional one.

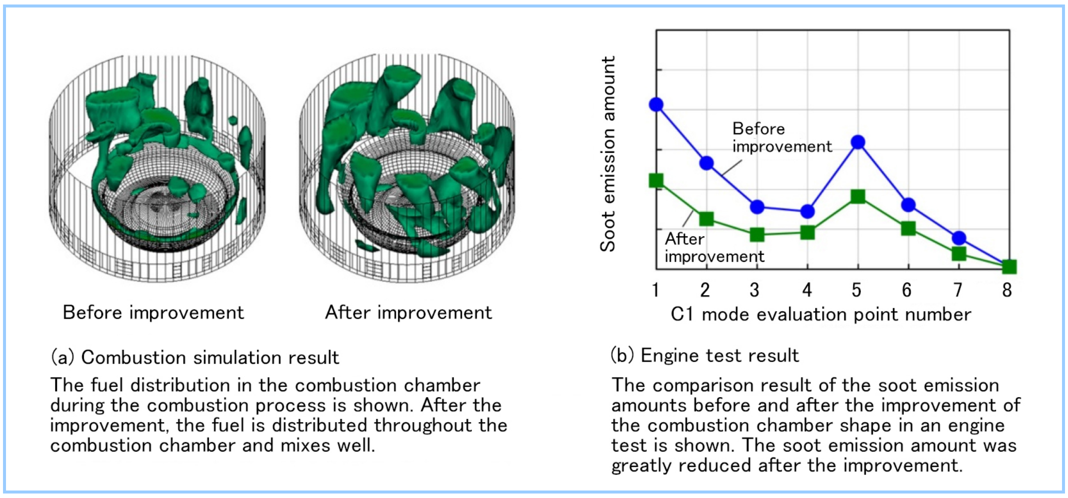

Figure 1 Reduction of soot emission amount due to improvement of combustion chamber shape

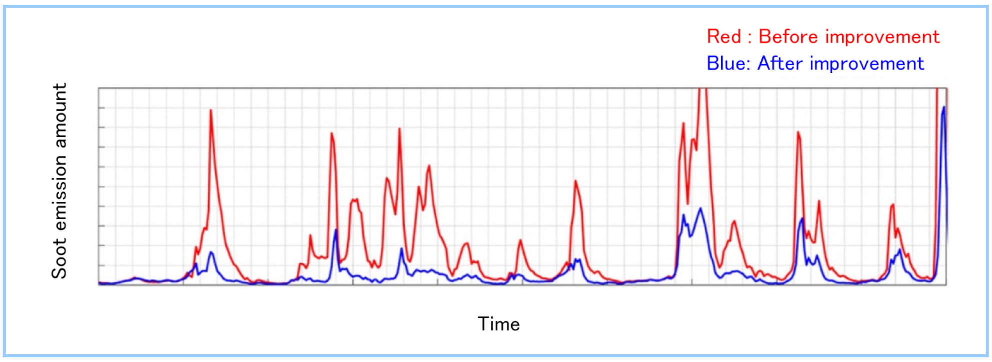

Figure 2 Evaluation of soot emission amount under in-market operating conditions

3.2 DPF regeneration control

DPF regeneration burns off soot accumulated inside the DPF for removal. For that purpose, it is necessary to control the exhaust gas temperature at a predetermined value to ensure an appropriate soot oxidation rate. In terms of controlling the exhaust gas temperature, it is favorable to install the DPF near the engine. On the other hand, installing the engine and DPF separately can make the equipment layout flexible. The developed engine and DPF can be installed separately in order to allow existing machines and vehicles to be easily equipped with an engine that complies with the EU Stage V emission standards. It was confirmed that good temperature control can be performed without being affected by the response delay due to the pipe length under any operating condition and that problems such as the fuel for DPF regeneration becoming excessive and being discharged in exhaust gas as-is and the exhaust gas temperature rising abnormally due to response delay, do not occur.

The exhaust temperature control for DPF regeneration is handled by adding and adjusting the fuel injection into the cylinder so that the temperature rises and by throttling the exhaust gas with the exhaust throttle value. The exhaust temperature at the DPF is adjusted so as to be maintained at the required constant temperature level regardless of the steady or transient operating conditions over a wide range of engine loads and engine speeds. In particular, by using the exhaust throttle value, it is possible to maintain the exhaust temperature required for DPF regeneration, including in low load and low speed regions.

As a result, we have established a control that can perform regeneration under almost all operating conditions as long as the engine is running after warming up and can complete DPF regeneration automatically while the engine is in use.

4. Evaluation under actual operating conditions

Since our industrial engines are used for various applications, we carried out the development so that DPF regeneration can be completed under any operating pattern. There are characteristic operating patterns depending on the application, so we investigated, in particular, the actual operation conditions of the forklift trucks to which the developed engine is to be installed and the evaluation of DPF regeneration was carried out on the engine bench and in the market.

4.1 Engine evaluation with evaluation patterns based on in-market operation data

In order to evaluate that DPF regeneration can be completed under any conditions without interfering with normal engine use, we conducted a preliminary survey of engine operating conditions in the market. The engines developed this time are to be installed in forklifts in particular, so the survey was conducted with the cooperation of Mitsubishi Logisnext Co., Ltd. We asked customers who actually use forklifts in their daily work to use forklifts equipped with an engine data logger in order to measure the engine operating status.

The operating status survey was conducted for multiple forklifts and customers, including every-millisecond-measurement of multiple data points on engine operating conditions such as engine speed, throttle opening, fuel injection quantity, engine coolant temperature and operating environment temperature. We acquired data for more than hundreds of hours of operating time in total. The data was analyzed focusing on the engine speed and fuel injection quantity (engine load) and characteristic operating patterns were identified and extracted. The acquired operation data was classified into extracted operating patterns according to the characteristics and the occurrence frequency of each operating pattern during actual operation in the market was arranged. **Figure 3** shows an example of actual operation data and the classification into operating patterns. By combining the operating patterns in proportions corresponding to their occurrence frequency, a DPF regeneration evaluation pattern that reflects the operation status in the market was created and used for evaluation on the engine bench. **Figure 4** is a DPF regeneration evaluation pattern created by combining the extracted operating patterns.

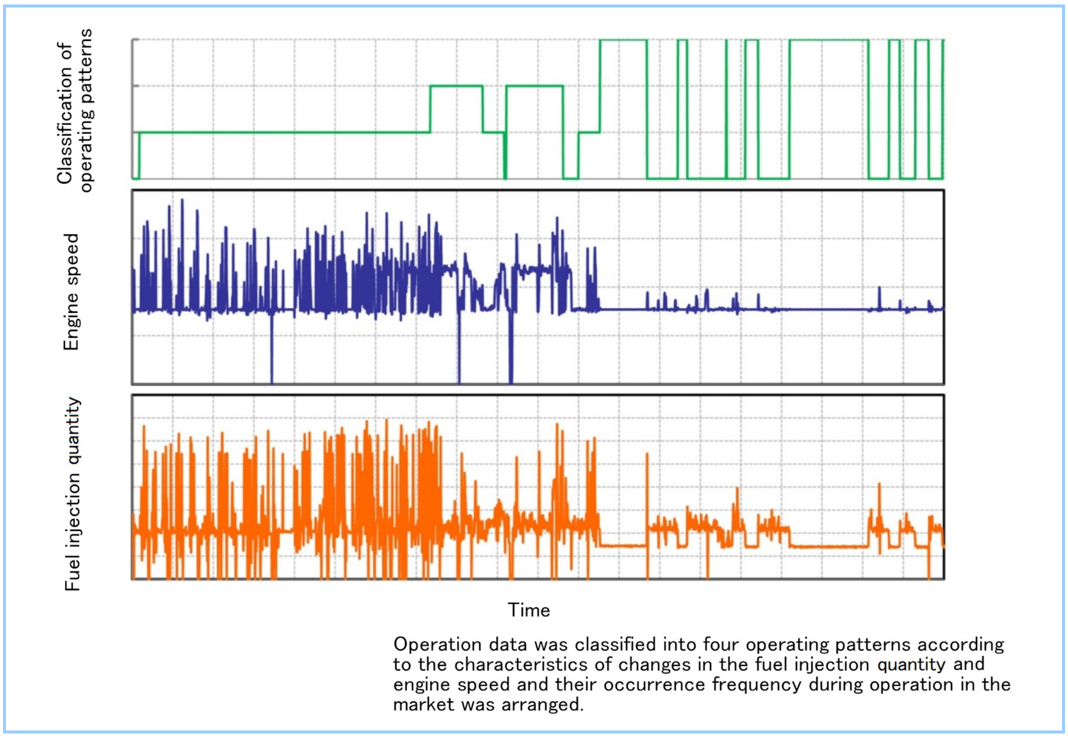

Figure 3 Analysis example of in-market operation data

We evaluated the engine operable time without DPF regeneration on an engine bench using multiple evaluation patterns including the created evaluation pattern. It was confirmed that the soot reduction implemented this time effectively reduced the required number of DPF regenerations per unit operating time to as little as less than half that of the conventional model. It was also confirmed as expected that DPF regeneration can be completed under any engine operating condition for multiple evaluation patterns including actual operating patterns in the market focusing on low speed and low load. **Figure 5** is an example in which it was confirmed that the exhaust temperature could be maintained constant at the required level and DPF regeneration was possible for the evaluation pattern.

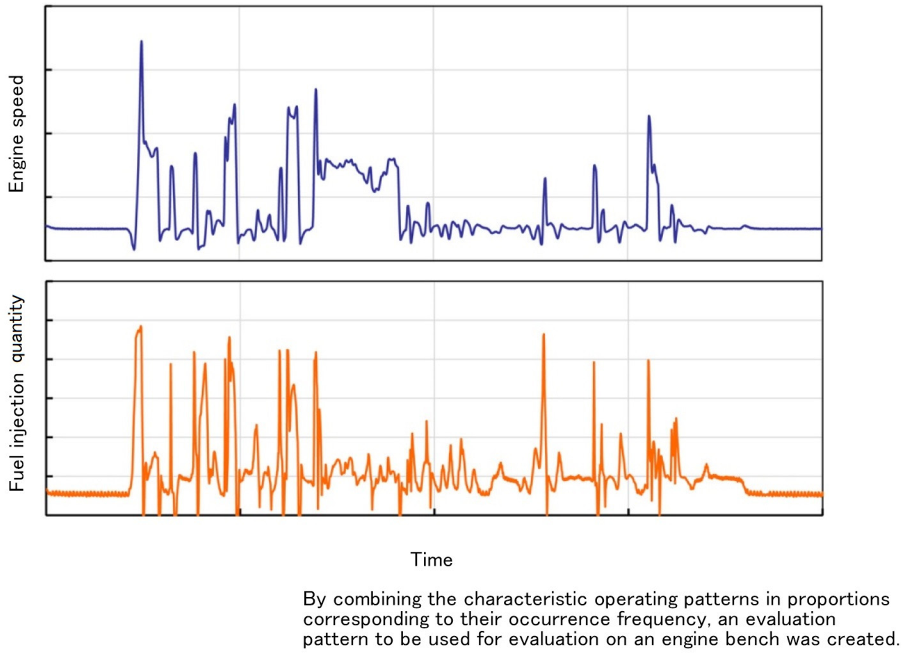

Figure 4 Example of evaluation pattern based on in-market operation data

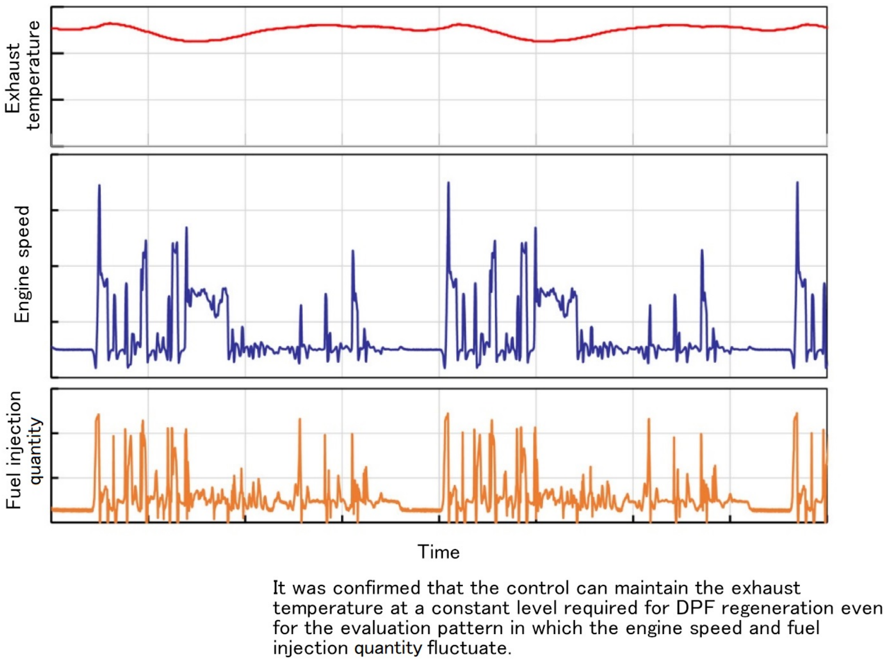

Figure 5 Exhaust temperature control in DPF regeneration based on evaluation pattern

4.2 Verification with field follow-up

Also with the cooperation of Mitsubishi Logisnext Co., Ltd., we installed an engine data logger on vehicles before their release and asked European customers to use them in the field in order to verify that the desired functions were realized. In advance of long-term operation in Europe, we prepared a system to monitor the local operation status on a computer in a domestic office with the data logger signal uploaded to the server via mobile phone line. We have checked the operating status data on multiple vehicles for several thousand hours in total and some vehicles are still operating today.

This verification checked the data under the actual operating conditions in the market focusing on [1] whether DPF regeneration could be completed under any operating condition and [2] whether the DPF regeneration interval was as long as expected.

It was confirmed by checking all the operation data that—also under actual operating conditions—DPF regeneration could be continued and completed under any operating condition except when the customer stopped the engine during operation and that there was no interruption of work for DPF regeneration. It was also confirmed that even when the engine was stopped during DPF regeneration, it could be resumed and completed without any problem after restarting the engine.

As a result of checking the total operating time and the number of times of DPF regeneration for each forklift, it was confirmed that the operating time until the moment when DPF regeneration was required was also the same as that obtained on the engine bench with the evaluation pattern in the development and that the DPF regeneration interval was extended to more than twice that of the conventional model.

5. Conclusion

For the adoption of DPF for engines to allow them to comply with the European Stage V emission standards, we carried out development aiming at reducing soot to extend the DPF regeneration interval and expanding the DPF regeneration range. In the evaluation of the developed engine, we incorporated evaluation patterns created based on the operation data measured in the market in addition to the existing evaluation methods, confirming that the target functions were achieved.

The developed engines have been mass-produced since 2020. We will continue to develop engines that consider actual market conditions and are convenient and attractive for customers.

References

(1) Hiraoka et. Al., Development of EPA Interim Tier 4 Certified Small Diesel Engine, Mitsubishi Heavy Industries Technical Review, Vol.50 No.1 (2013) p.60～65