Technical Paper

Compliance with Tier 4 Final Emissions Regulations Development of 125 mm and 140 mm Bore Engines

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Tier 4 Final emissions regulations, effective from January 2014, require that nitrogen oxides (NOx) in emissions be reduced by 80% over the level required by the previous standards. In just three years from the implementation of Tier 4 Interim emissions regulations in January 2011, new 11-liter and 15-liter engines with new technologies were developed and launched that meet the latest, much more stringent emissions regulations while maintaining the same or better performance, durability and reliability over the previous engines. This paper introduces these new engines.

Key Words: *Construction Equipment, Diesel Engine, Emissions Regulations, NOx Reduction Aftertreatment System, Urea Solution*

1. Introduction

Diesel engines are used for a wide range of industrial applications as they are highly durable and reliable, are available in various sizes from small to large, therefore offering various power ranges, and have high thermal efficiency. On the other hand, nitrogen oxides (hereafter "NOx") and particulate matter (hereafter "PM") that are emitted from diesel engines are known to have negative impact on the environment and organisms.

Since 1996, as part of efforts to stem the impact, emissions regulations for diesel engines on construction equipment have been made increasingly stringent worldwide. These efforts, particularly in construction and mining, have been led by the Japanese, US and European authorities.

To clear EPA Tier 4 Final and EU Stage IV regulations, both effective since January 2014, and Japan's off-road emissions regulations for designation of low-emission construction equipment which became effective in October 2014 (hereafter the underlined parts are collectively referred to as "Tier 4 Final emissions regulations"), the new engines that are described in this paper incorporate the existing, and now upgraded, proven technologies that were originally introduced to clear EPA Tier 4 Interim and EU Stage III B regulations, both put in place in January 2011, and Japan's off-road emissions regulations for designation of low-emission construction equipment which became effective in October 2011 (hereafter the underlined parts are collectively referred to as "Tier 4 Interim emissions regulations"). In addition to these technologies, the new engines employ a new aftertreatment technology for NOx reduction. This paper provides an overview of Komatsu's new 11-liter and 15-liter engines compliant to Tier 4 Final emissions regulations, focusing on their technical features.

2. Emissions regulations for diesel engines on construction equipment

As described above, emissions regulations for diesel engines on construction equipment were made more stringent in 2014 with the introduction of Tier 4 Final.

Fig. 1 shows the past and planned emissions regulations for Japan, US and Europe.

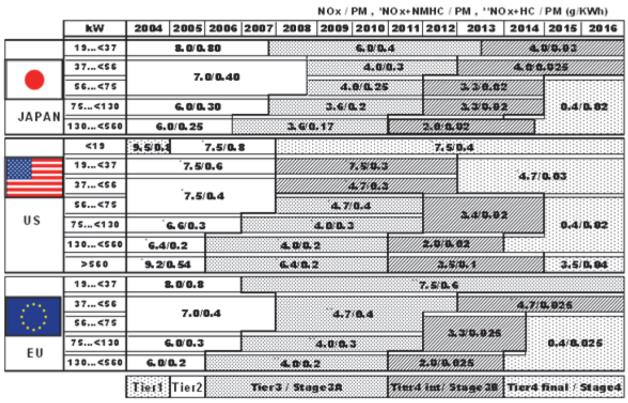

Fig. 1 Emissions standards in Japan, US and Europe

Fig. 2 shows a historical review of EPA standards on NOx and PM from Tier 1 to Tier 4. Standards have been made more stringent every five years, with NOx, PM and other key contaminants required to be cut by around 30% at every Tier progression. Tier 4 Interim, introduced in January 2011, required a 50% reduction in NOx and a 90% reduction in PM from Tier 3. Komatsu cleared the Tier 4 Interim hurdles with the introduction of a new aftertreatment system and other techniques.

Tier 4 Final requires an 80% reduction in NOx while maintaining the same standard for PM. Komatsu meets the requirement with the introduction of an NOx reduction aftertreatment technology.

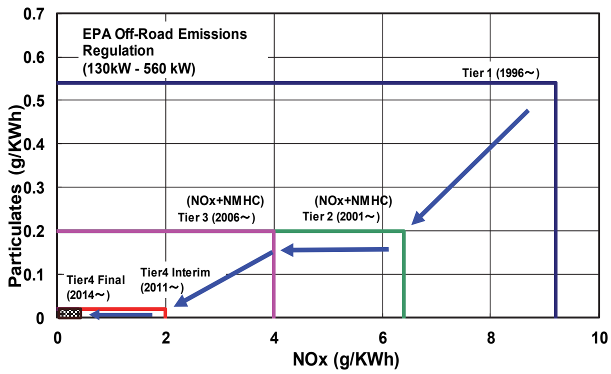

Fig. 2 Historical review of EPA emissions standards

Emissions from diesel engines on construction equipment have traditionally been measured in steady-state 8 modes, or C1 mode in ISO 08178.

With Tier 4 Interim, introduced in 2011, came a new measurement requirement. That is nonroad transient cycle test. Emissions now need to be measured in both of these modes and clear the standards.

To clear the nonroad transient cycle measurement standards in Tier 4 Final, it is extremely important for the new NOx reduction aftertreatment system to operate highly accurately.

Fig. 3 shows the current methods for measuring emissions from construction equipment diesel engines.

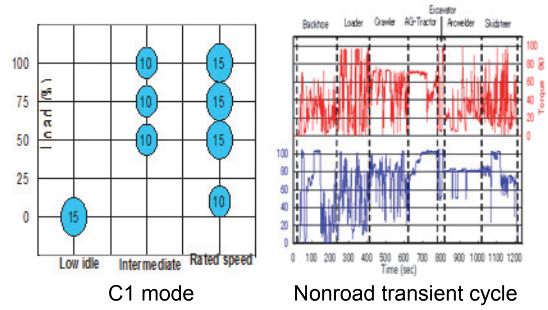

Fig. 3 Methods for measuring emissions from construction equipment diesel engines

3. Overview of Tier 4 Final-compliant 125 mm and 140 mm bore engines

(1) 11-liter and 15-liter engines

As described earlier, Tier 4 Final emissions regulations have been effective since January 2014 in US and Europe and October 2014 in Japan. Of the Tier 4 Final-compliant engines below 560 kW developed specifically to meet the new standards, this paper describes 11-liter and 15-liter engines.

Fig. 4 shows the displacements and power ranges of these engines. **Fig. 5** shows some of the key construction equipment on which these engine are mounted.

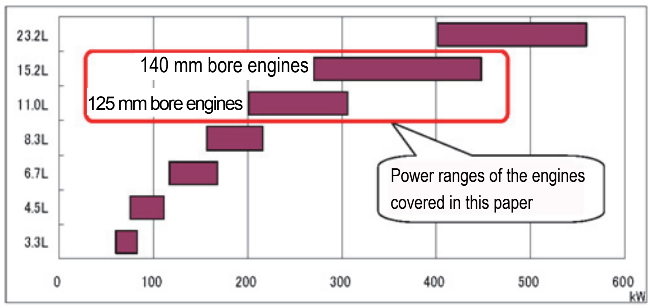

Fig. 4 Engine displacements and power ranges

Fig. 5 Key applications for the 125/140 mm bore engines

(2) Objectives in the development of Tier 4 Final-compliant engines

(a) Clear Tier 4 Final emissions regulations in Japan, US and Europe
(b) Same or less fuel consumption than the previous engines while minimizing the consumption of urea solution
(c) Minimize changes to the base engine design and utilize the existing Tier 4 Interim ancillary technologies
(d) Maintain durability and reliability in demanding operating conditions

Table 1 shows the technologies incorporated to clear the emissions regulations. **Table 2** shows some of the key technologies employed to meet the objectives.

Table 1 Technologies to clear emissions regulations

Regulations	Technology
Tier 2	(1) Air cooled aftercooler + (2) High pressure fuel injection (120 MPa)
Tier 3	(1) Air cooled aftercooler + (2)' High pressure fuel injection (160 MPa) + (3) Exhaust Gas Recirculation
Tier 4 Interim	(1) Air cooled aftercooler + (2)" High pressure fuel injection (200 MPa) + (3)' Exhaust Gas Recirculation + (4) Variable geometry turbocharger + (5) Komatsu Diesel Particulate Filter
Tier 4 Final	(1) Air cooled aftercooler + (2)" High pressure fuel injection (200 MPa) + (3)' Exhaust Gas Recirculation + (4) Variable geometry turbocharger + (5)' Komatsu Diesel Particulate Filter + (6) Selective Catalytic Reduction

Table 2 Key technologies on the 11-liter and 15-liter engines

		Tire 4 Interim		Tier 4 Final	
Engine model	unit	SAA6D125E-6	SAA6D140E-6	SAA6D125E-7	SAA6D140E-7
No. of cylinders	–	6			
Bore x Stroke	mm	125×150	140×165	125×150	140×165
Displacement	L	11.04	15.24	11.04	15.24
Fuel injection	–	Common rail system			
Max. fuel injection pressure	MPa	180	200	180	200
Combustion chamber	–	New combustion chamber		←	
Turbocharger	–	Variable geometry		←	
Exhaust Gas Recirculation	–	Standard (Fins & Tubes)		←	
Controller	–	CM2250		CM2350	
Blow-by gas	–	Positive crankcase ventilation		←	
Aftertreatment	–	Komatsu Diesel Particulate Filter		Komatsu Diesel Particulate Filter+Selective Catalytic Reduction	

In the new engine development project, the biggest hurdle was to develop a selective catalytic reduction system to reduce NOx by at least 80%.

To complete the project within the shorter, 3-year period and ensure the same or better engine performance, durability and reliability over the previous engines, Komatsu's proven Tier 4 Interim technologies have been retained for the base engine parts and other key areas.

The key technologies incorporated in the new engines include electronically controlled common rail system that operates at higher pressure, variable geometry turbocharger, more accurately controlled exhaust gas recirculation valve, larger exhaust gas recirculation cooler, and Komatsu Closed Crankcase Ventilation that sends blow-by gas back to the air intake system without releasing it out to the atmosphere.

Fig. 6 shows the SAA6D125E-7 engine for hydraulic excavators. **Fig. 7** shows the SAA6D140E-7 engine for dozers.

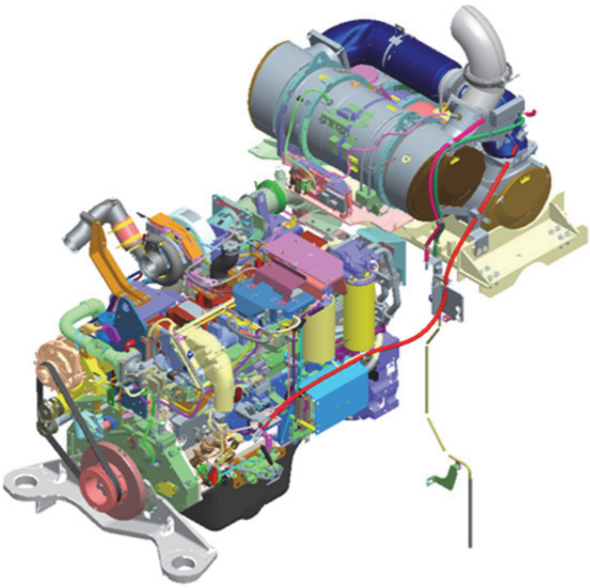

Fig. 6 Tier 4 Final-compliant SAA6D125E-7 engine

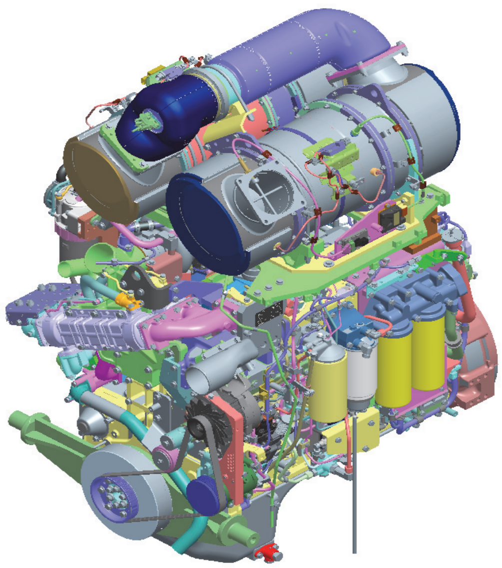

Fig. 7 Tier 4 Final-compliant SAA6D140E-7 engine

4. Tier 4 Final-compliant engine technologies

The following paragraphs describe the key components of the Tier 4 Final-compliant engines that contribute to clearing the latest emissions regulations in Japan, US and Europe, and at the same time offering the same or better performance (in power and fuel consumption) over the previous engines, which is one of the new engine development objectives.

(1) Combustion system

The electronically controlled common rail fuel injection system with maximum injection pressure of 200 MPa and the new combustion chamber, both originally introduced on the Tier 4 Interim engines, have been retained on the new engines, which were then tuned for maximum performance. With the addition of a selective catalytic reduction system in the after-treatment system, the new engines achieve the same or less fuel consumption and the same level of PM emission over the previous engines, although urea solution consumption has been added. **Fig. 8** shows a comparison of fuel consumptions by 15-liter engines.

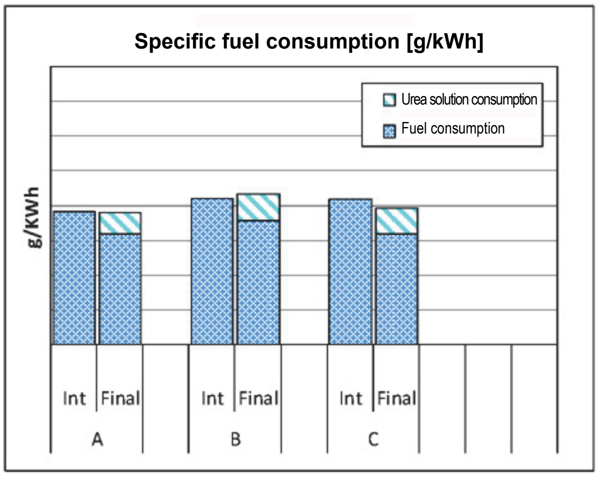

Fig. 8 Comparison of fuel consumptions by 15-liter engines

(2) Exhaust gas recirculation valve

The hydraulically driven exhaust gas recirculation valve with a hydraulic servo system, developed for the Tier 4 Interim-compliant engines, has been retained. **Fig. 9** shows an external view of the compact, highly accurate and reliable exhaust gas recirculation valve.

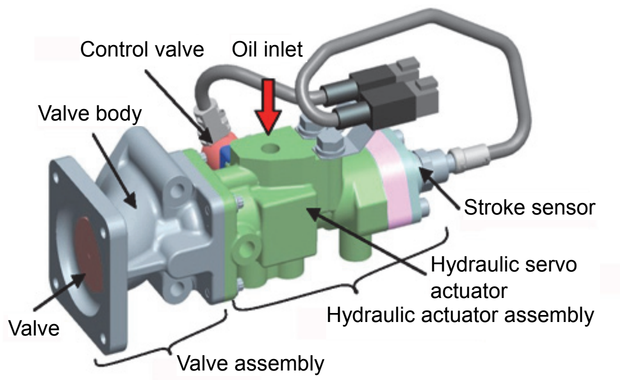

Fig. 9 External view of the exhaust gas recirculation valve

(3) Exhaust gas recirculation cooler

Fig. 10 shows the external view and structure of the high capacity exhaust gas recirculation cooler developed for the

Tier 4 Interim-compliant engines. To substantially reduce NOx, it is essential to sufficiently cool exhaust gas being recirculated in large volume.

To achieve that, the previous multitubular design has been changed to the new design of fins and tubes where fins are arranged between the tubes in the gas channel.

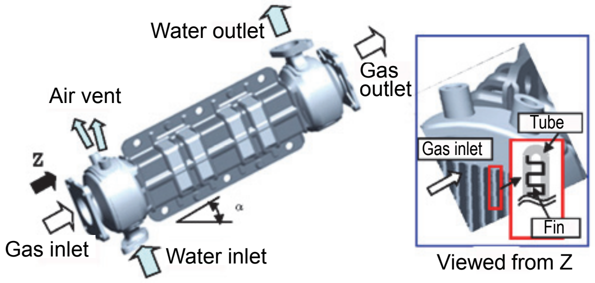

Fig. 10 External view and structure of the exhaust gas recirculation cooler

(4) Variable geometry turbocharger

The variable geometry turbocharger with a sliding-nozzle design to vary the channel size, developed for the Tier 4 Interim-compliant engines, has been retained.

As with the exhaust gas recirculation valve described earlier, Komatsu's exclusive hydraulic drive technology is used to move the sliding system.

The variable geometry design enables exhaust gas recirculation across a wide operating range, helping to improve fuel consumption and acceleration and thus contributing greatly to overall product performance upgrade. **Fig. 11** shows the structure of the variable geometry turbocharger.

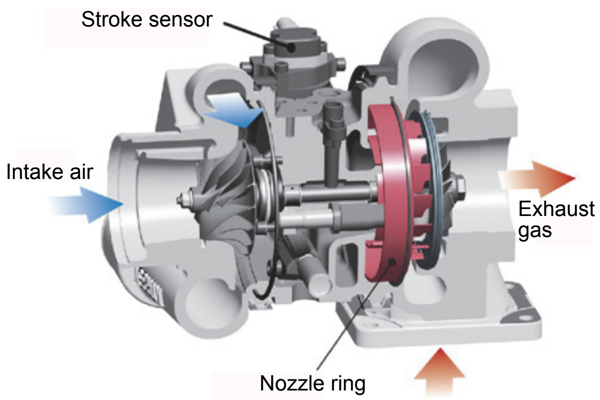

Fig. 11 Structure of the variable geometry turbocharger

(5) Komatsu Closed Crankcase Ventilation

The Komatsu Closed Crankcase Ventilation system, developed for the Tier 4 Interim-compliant engines, has been retained.

The compact, highly reliable Komatsu Closed Crankcase Ventilation filter features a highly rigid aluminum body which can withstand severe operating conditions of construction equipment, a pressure regulating valve which prevents crankcase pressure drop caused by vacuum upstream of the turbo inlet, and a pressure sensor for detecting a clogged filter. **Fig. 12** shows the external view of the Komatsu Closed Crankcase Ventilation system.

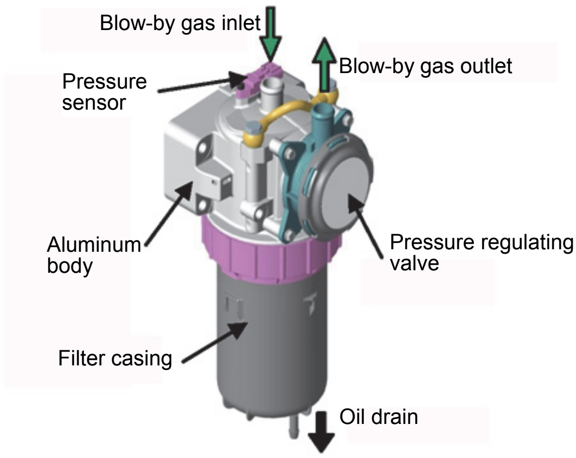

Fig. 12 External view of the Komatsu Closed Crankcase Ventilation system

5. Aftertreatment system

The Komatsu Diesel Particulate Filter was developed for our Tier 4 Interim-compliant engines to capture and remove soot in exhaust gas.

Fig. 13 shows the internal structure of the filter.

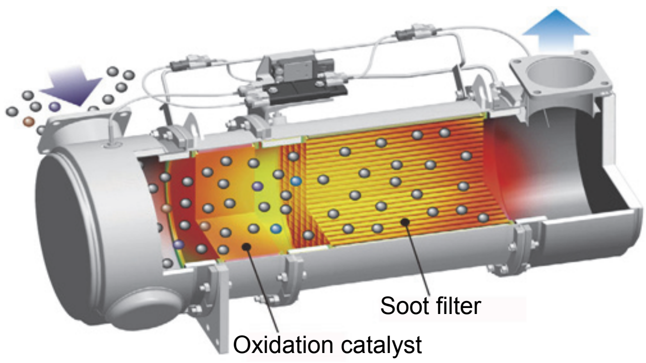

Fig. 13 Structure of the Komatsu Diesel Particulate Filter

In addition to the Komatsu Diesel Particulate Filter, to reduce NOx by at least 80%, a requirement in Tier 4 Final emissions regulations, the new engines are equipped with a urea selective catalytic reduction system.

The system breaks down NOx in exhaust gas into harmless nitrogen (N_2) and water (H_2O).

As shown in **Fig. 14**, urea solution is injected into exhaust gas, and NOx reacts with ammonia in the solution within the selective catalytic reduction catalyst and is broken down into nitrogen and water.

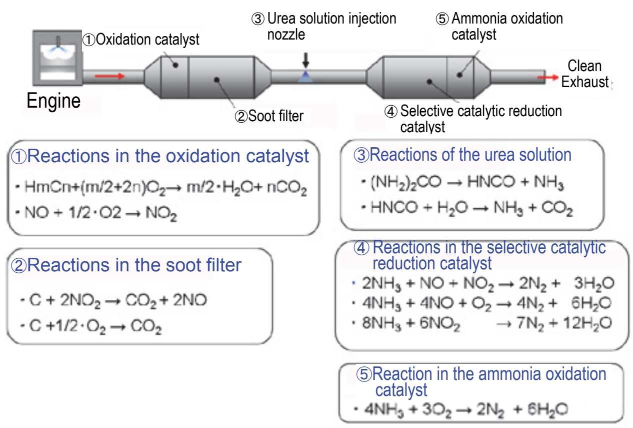

Fig. 14 Chemical reactions in urea selective catalytic reduction

As shown in **Fig. 15**, the urea selective catalytic reduction system primarily consists of the urea solution distribution system which injects urea solution into exhaust gas, the urea solution mixing line which breaks down the injected urea solution into ammonia and dissipates the ammonia in exhaust gas, and the selective catalytic reduction assembly which houses the selective catalytic reduction catalyst that facilitates the dissolution of NOx.

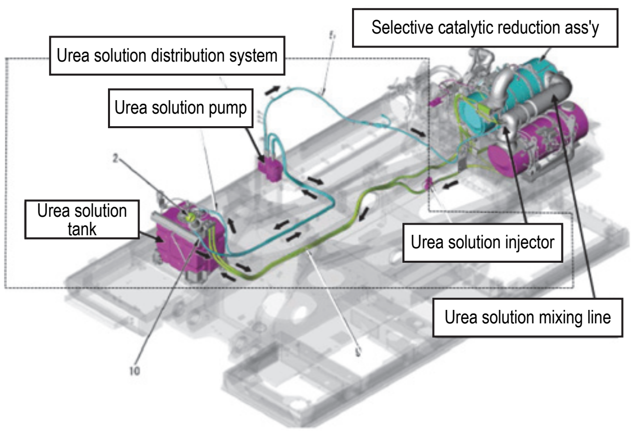

Fig. 15 Urea selective catalytic reduction system is equipped

(1) Urea solution distribution system

The urea solution distribution system consists of the urea solution tank, the urea solution pump and the urea solution injector.

Urea solution is pressurized by the urea solution pump and is injected by the urea solution injector into exhaust gas. If the amount of urea solution injected into exhaust gas is too small, not all NOx is broken down and the NOx that remains undissolved is discharged into the atmosphere. If the amount of urea solution injected into exhaust gas is too much, the excessive urea solution forms deposits of urea in the exhaust pipe while the excessive ammonia is discharged into the atmosphere.

Engine speed and power change as load on the construction machine on which the engine is mounted changes. And as that happens, the amount of NOx in exhaust gas changes accordingly. The urea solution distribution system keeps monitoring the operating status of the engine and selective catalytic reduction assembly to ensure that appropriate amounts of urea solution are injected at all times.

The urea solution freezes at -11˚C. To be able to thaw the solution or keep it warm enough for machines working in freezing conditions, the hosing going out and into the urea solution tank and pump incorporates heating wire.

(2) Urea solution mixing line

In the urea solution mixing line, urea solution that has been injected into exhaust gas is broken down into ammonia and dissipated evenly in the exhaust gas before reaching the selective catalytic reduction catalyst. If the mixing line has a complex internal structure to dissipate ammonia evenly, deposits of urea can form inside the mixing line. To prevent that and achieve even and efficient dispersion in a limited space on a construction machine, the internal structure of the mixing line has been designed appropriately using computational fluid dynamics analysis. **Fig. 16** shows an example of computational fluid dynamics analysis for the mixing line.

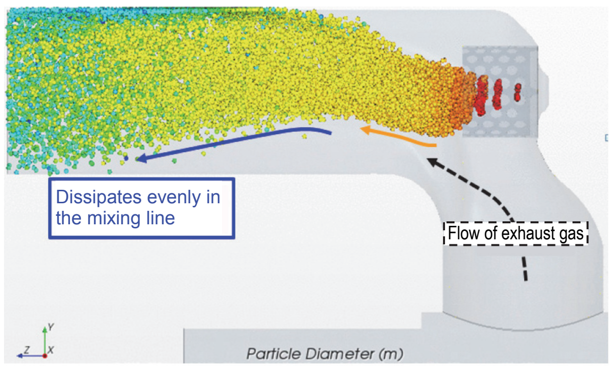

Fig. 16 Example of computational fluid dynamics analysis for the mixing line

(3) Selective catalytic reduction assembly

The selective catalytic reduction assembly houses the selective catalytic reduction catalyst which allows NOx in the exhaust gas and ammonia generated through the dissolution of urea solution to react with each other and facilitates the dissolution of the NOx into harmless nitrogen and water. In the process, ammonia adheres to the selective catalytic reduction catalyst and NOx in the exhaust gas reacts with the ammonia, as shown in **Fig. 17**.

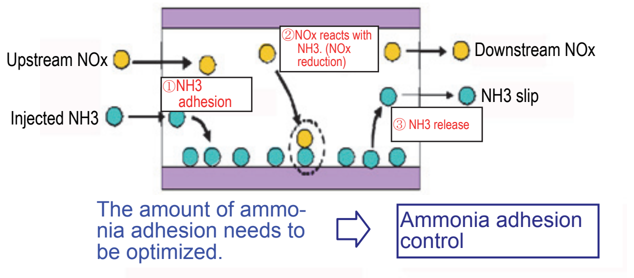

Fig. 17 Reduction of NOx by the selective catalytic reduction catalyst

By increasing the amount of ammonia that adheres to the selective catalytic reduction catalyst, more NOx can be reduced. Onboard sensors are used to monitor the operating status of the selective catalytic reduction assembly, and based on the input from the sensors including the amount of ammonia adhering to the catalyst, the amount of ammonia that reacts with NOx and the amount of NOx coming from the engine, the optimum injection volume of urea solution is determined.

An ammonia oxidation catalyst is provided downstream of the selective catalytic reduction catalyst to prevent unreacting ammonia from being released out the exhaust pipe into the atmosphere.

As with the oxidation catalyst and soot filter in the Komatsu Diesel Particulate Filter, these catalysts are carried on ceramic substrates, which are held in place by a mat made of special, highly heat resistant fiber and housed in a metal casing. This design is modeled after the Komatsu Diesel Particulate Filter that was launched in 2011 and has since proven its high durability and reliability in the severe, shock load-prone operating environment of construction equipment.

Fig. 18 shows the internal structure of the selective catalytic reduction assembly.

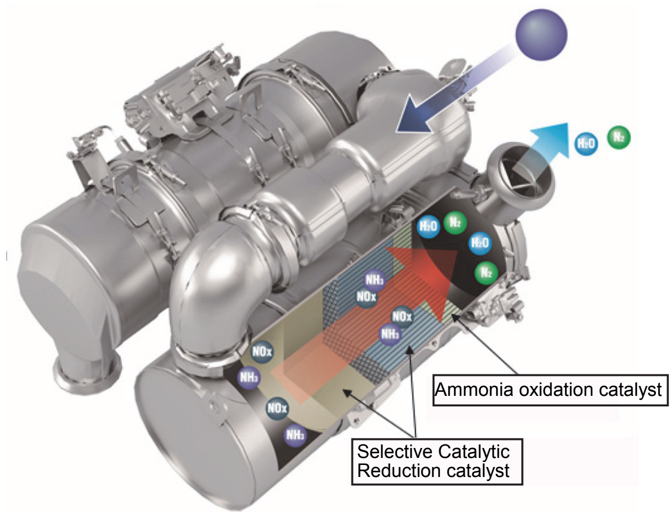

Fig. 18 Internal structure of the selective catalytic reduction assembly

Generally, construction equipment operates under repetitive load more than commercial vehicles and passenger cars, causing its exhaust gas to be hotter, thus facilitating chemical reactions more easily in aftertreatment. The Komatsu Diesel Particulate filter, urea mixing line and selective catalytic reduction assembly are all heat insulated to minimize temperature drop inside these units, thus maximizing the effect of hot exhaust gas. Even in light load applications and low ambient temperature, the heat insulation design helps maximize the units' PM and NOx reducing performance.

The Komatsu Diesel Particulate filter, urea mixing line and selective catalytic reduction assembly are all manufactured at Komatsu to ensure high quality.

6. Electronic control system

With the Tier 4 Final-compliant engines, the urea selective catalytic reduction system has been added to the electronic control system to enable its highly accurate control. A newly developed engine control unit has replaced its predecessor to ensure coordinated control of the selective catalytic reduction system with the Tier 4 Interim-compliant technologies including the electronically controlled common rail fuel injection system, variable geometry turbocharger and Komatsu Diesel Particulate Filter and to maintain optimum high-speed communication between these units and other onboard electronic systems.

To meet the selective catalytic reduction inducement requirements under Tier 4 Final regulations, engine and aftertreatment diagnostics has been introduced to upgrade the troubleshooting system and minimize downtime.

7. Durability and reliability

As part of the development process of Tier 4 final-compliant engines, not only the quality verification codes, developed over the years, for industrial engines were met but new test codes were set up and related test conducted for the aftertreatment system including the new urea selective catalytic reduction system to ensure high quality, durability and reliability.

To verify the durability of the aftertreatment system including the new selective catalytic reduction assembly and urea mixing line in all perceived applications, test conditions were set up and related test conducted for vibration and impact acceleration using actual vehicle types on which the system was to be mounted.

Using a model of the complete aftertreatment system shown in **Fig. 19**, Eigen value problems were solved using the finite element method for an optimum structural design.

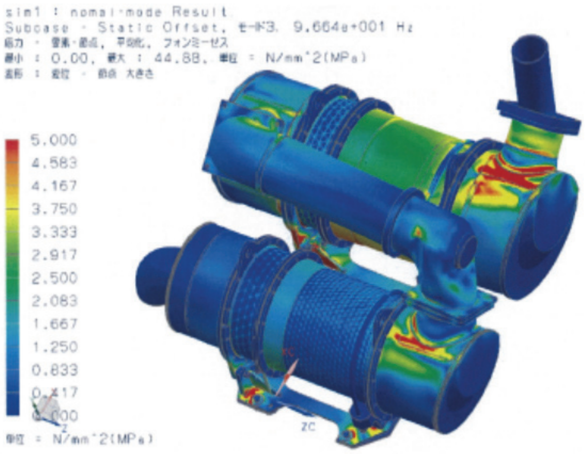

Fig. 19 Results of Eigen value problem solving using the finite element method for the aftertreatment system

As part of the verification process, vibration test was conducted for durability assessment on an aftertreatment unit as shown in **Fig. 20**.

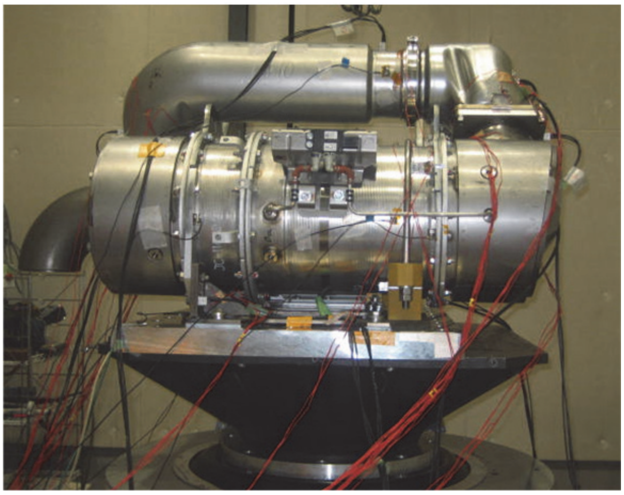

Fig. 20 Vibration test on an aftertreatment unit for durability assessment

As part of engine durability test, to verify that the Komatsu Diesel Particulate Filter and urea selective catalytic reduction system keep working efficiently in various applications and that the newly developed control parameters are relevant, simulated cycle test was conducted for durability assessment in all perceived typical working conditions to observe soot accumulation and urea deposit formation.

The 11-liter and 15-liter engines underwent more than 10,000 hours of bench test for durability assessment and more than 5,000 hours of onboard field test, from which these engines were proven to be sufficiently durable and reliable.

8. Conclusions

This paper provides an overview of the newly developed 11-liter and 15-liter engines, focusing on their technical features that are compliant to Tier 4 Final emissions regulations.

To meet the needs of the construction equipment market with products differentiated from other competing brands, most of the key, Tier 4 Final-compliant components were developed by Komatsu, and most of these in-house developments will be manufactured at Komatsu.

These engines together with the machines they are mounted on offer, as a product package, not just high fuel efficiency, durability and reliability but high quality for which Komatsu is known, with utmost considerations to the environment.

References:
"Construction methods and planning - Emissions regulations-compliant technologies in Japan, US and Europe"
"Komatsu Technical Report: Development of ϕ125 and ϕ140 Engines Meeting Tier 4 Interim Regulation"
"Construction equipment applications: Development of Tier 4 Final emissions regulations-compliant engines"

Introduction of the writers

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[A few words from writers]

The biggest hurdle in the development of the Tier 4 Final-compliant engines was to develop the aftertreatment system for NOx reduction.

These engines have already been launched in the market. We will keep closely monitoring the market for its evaluation of the new engines. We are also keen to know what the next level of emissions regulations will be and how we can clear these regulations with our technologies.