Technical Paper

Development of 4D95 Engine Series Meeting Tier3

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The ecot3 engine has been developed and sold on the market as a Komatsu engine series that complies with the Tier3 exhaust gas regulation. Komatsu has recently completed the development and market entry of its 4D95 engine series as the anchor engines in the series. Not only exhaust gas regulation, but also low noise and a high fuel consumption efficiency are the important missions in engine development as social demands. The 4D95 engine series accomplishes these missions and features a good balance without sacrificing the engine placement property in the vehicle and versatility, which are other missions of the small engine, by incorporating the state-of-the-art technology to clear the exhaust gas regulation.

Four models in the 4D95 engine series are overviewed and their technical features are introduced.

Key Words: *Diesel engine, environmentally friendly, Tier3, electronic control, common rail system, swirl current chamber system*

1. Background

Komatsu has successively developed and commercialized its engine ecot3 complying with the Tier3 exhaust gas regulations. The production of an engine series with a piston displacement of 4.5 to 23 liters covering an output range of 75 to 560kW had been completed by early 2006. Subsequent to the production of this engine series, the production of the 4D95 engine series (piston displacement of 3.3 liters) representing the smallest piston displacement in the engine series of Komatsu has recently been completed.

The 4D95 engine series complying with the Tier2 exhaust gas regulation has covered the output range of 40 to 75kW by a combination of three aspirations (NA [naturally aspirated engine], T [with turbo] and TAA [with turbo and air-cooled aftercooler]) and a mechanical fuel injection pump. To comply with the stricter Tier3 exhaust gas regulation, however, a specification to equip an electronically controlled high-pressure injection system (common rail system) has been added, to cover the output range of 82kW maximum. Taking the installability and versatility into consideration, the specification that covers the same output range as that of the Tier2 exhaust gas regulation continuously uses the mechanical fuel injection pump. To comply with the emission regulation, the combustion system of the NA and T specifications has been changed to the swirl current chamber system (IDI - indirect injection).

This paper overviews the 4D95 series, which is regarded as the anchor engines in the Komatsu ecot3 series, and describes its technical features.

2. Trends of Emission Regulation for Construction Machinery Engines

As mentioned above, the emission regulations on diesel engines for construction machinery include the so-called Tier3 exhaust gas regulation centered in Europe and the United States and on/off-load Tier3 exhaust gas regulation of Japan for construction machinery.

Figure 1 plots changes in the regulation values for NOx + NMHC and PM emissions under Tier1, Tier2, Tier3 and Tier4 exhaust gas regulations corresponding to 56kW - 75kW in the 4D95 series using the EPA regulation of the United States as an example. Macroscopically, principal regulation values such as for NOx and PM are required to be gradually reduced by a level of about 30%. Comparing the EPA Tier1 regulation level of the United States enforced at the beginning of 1996 and EPA Tier3 regulation started in 2007 or 2008 spanning a period of about ten years, exhaust gas emissions are reduced to about one half. In the span of about 20 years to 2015 when Tier4 will be enforced, the emission level will be reduced to about 1/20.

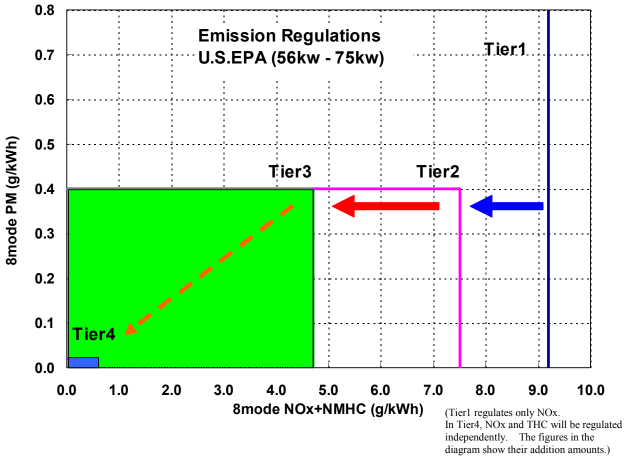

Fig. 1 History of NOx + NMHC and PM emission levels

3. Overview of 4D95 Engine Series

The 4D95 engine series comprises engines that have four cylinders, a bore diameter of 95mm, stroke of 115mm and total piston displacement of 3.3 liters, or the smallest in piston displacement in the ecot3 engine series of Komatsu. **Figure 2** plots the relationship between total piston displacement and the rated output range of the Komatsu ecot3 engine series. The principal specification of the 4D95 engine series is summarized in **Table 1**.

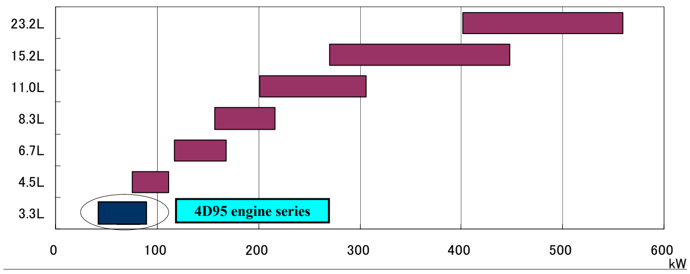

Fig. 2 Komatsu ecot3 engine series

Table 1 Principal specification of 4D95 engine series

Model	unit	4D95LE-5	S4D95LE-5	SAA4D95LEM-5	SAA4D95LE-5
Cylinders	–	4			
Bore diameter × stroke	mm	95×115			
Piston displacement	L	3.3			
Output range	kW	40–48	42–55	56–63	50–82
Air intake system	–	NA	T	TAA (CAC)	TAA (CAC)
Combustion system	–	IDI	IDI	DI	DI
Combustion chamber	–	–	–	2-stage combustion chamber	2-stage combustion chamber
Fuel injection system	–	Distributor type pump	Distributor type pump	Distributor type pump	Common rail system
Max. injection pressure	MPa	30	30	65	110
Compression ratio	–	21.0	20.8	19.0	17.3
Turbo charger	–	Not provided	Standard turbo	High pressure ratio turbo	High pressure ratio turbo
Pressure ratio	–		1.4	2.4	2.4
Control	–	Mechanical	Mechanical	Mechanical	Electronic control
EGR	–	Not provided	Not provided	Not provided	Not provided

3.1 Overview of SAA4D95LE-5 engine

The SAA4D95LE-5 engines cover the high output range in the 4D95 engine series. As in the medium and large engine series, the SAA4D95LE-5 engine employs the electronic control and high-pressure common rail system (HPCR). On the other hand, aiming at complying with the Tier3 exhaust gas regulation that does not require EGR, the regulation is complied by equipment of an air-cooled aftercooler and by improving combustion mainly by modifying the shape of the combustion chamber. **Figure 3** shows an appearance of the SAA4D95LE-5 engine. The technologies incorporated in the engine are described.

The engine will be equipped in the PC138-8 and other construction machines of Komatsu.

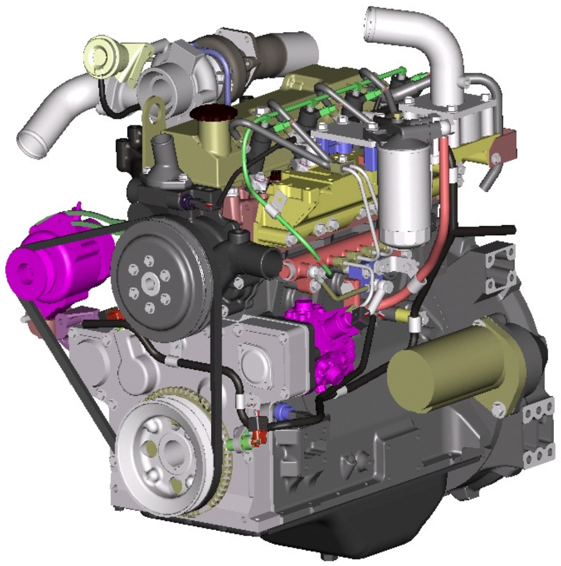

Fig. 3 Appearance of SAA4D95LE-5 engine

3.1.1 Common rail system

The common rail system has the highest potentials among the various injection systems, featuring high-pressure injection and a high degree of freedom of injection time. Komatsu quickly equipped the common rail injection system in its medium and large diesel engines for construction machines. Quality verification required for construction machinery was conducted and modification was incorporated in every detail of the common rail system, to be built with high reliability and durability.

A small common rail system has been developed in the SAA4D95LE-5 engine by further modifying it for small engines.

An appearance of the new small common rail system is shown in **Figure 4**.

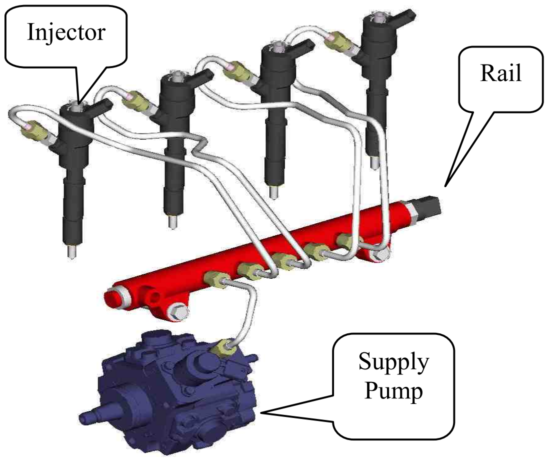

Fig. 4 Full view of small common rail system

3.1.2 Supercharger and air-to-air air-intake cooling system

The SAA4D95LE-5 engine incorporates Komatsu's key technology of the Komatsu ecot3 engine series, the air-to-air air-intake cooling system. The system is designed to increase the weight flow of intake air into the engine cylinders and to lower the intake air temperature. The system cools air, which is heated by supercharging by a turbocharger, by heat exchanging with outside air. This allows lowering of the combustion temperature; that is, reducing NOx while maintaining high performance.

The turbocharger features a high-pressure ratio and high efficiency by optimizing the shape of the compressor blades and modifying the air intake port.

3.1.3 New combustion system

The SAA4D95LE-5 engine has a new combustion system mainly aimed at improving combustion. The piston has one large cavity and one small cavity, contributing to the reduction of NOx in the early stage of combustion and PM, in the latter part of it. As a result, emissions could be reduced without drastically increasing the combustion time. **Figure 5** shows an appearance of the combustion chamber of the new combustion system.

Fig. 5 Shape of combustion chamber for SAA4D95LE-5 engine

The emission performance and engine body noise of the SAA4D95LE-5 engine are plotted in **Figures 6** and **7**. The NOx + NMHC and PM levels of the Tier3 exhaust gas regulation have been complied with an ample margin. A similar fuel consumption ratio as that of an engine that complies with the Tier2 exhaust gas regulation has been secured.

A noise level about 1 to 2dB(A) lower in all the operation speed range could be achieved compared with engines that complies with the Tier2 exhaust gas regulation utilizing the characteristics of the common rail system by multi-injection and other means.

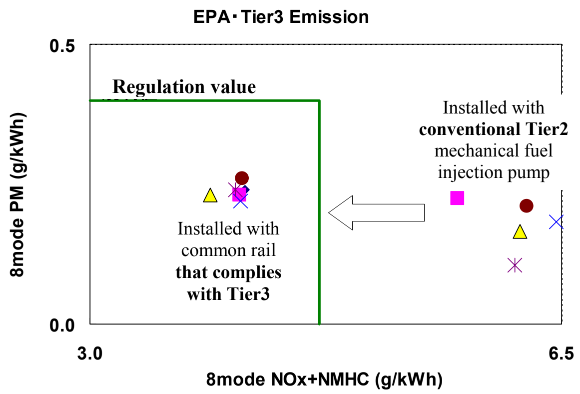

Fig. 6 Emission performance of SAA4D95LE-5 engine

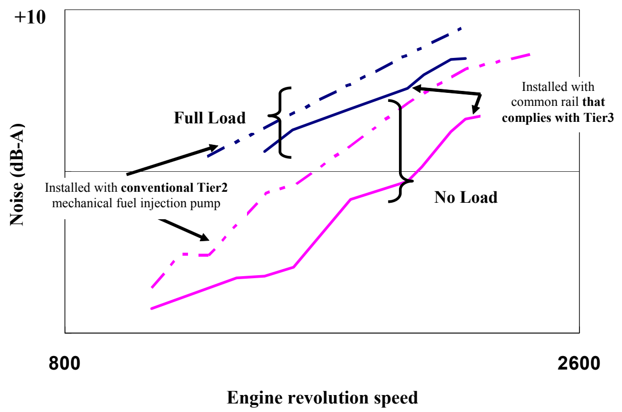

Fig. 7 Noise of SAA4D95LE-5 engine body

The new combustion system complies with the Tier3 exhaust gas regulation without the help of the EGR (exhaust gas recirculation) technology that is already used in medium and large engines. Compared with the ECM (engine control module) for medium and large engines that equips the EGR technology, the ECM for the SAA4D95LE-5 engine has been simplified by omitting the EGR drive part, thereby contributing to cost competitiveness, which is an important factor for small engines.

3.2 SAA4D95LEM-5 engine

The basic design of the SAA4D95LEM-5 engine is the same as that of the SAA4D95LE-5 engine mentioned in section 3.1 and covers the output range of 56 to 63kW equipped with a mechanical fuel injection pump. The mechanical fuel injection pump does not offer high-pressure injection, multiple injection and a high degree of freedom of injection time. The Tier3 exhaust gas regulation could be complied therefore by tuning the combustion chamber compared with the new combustion system for the SAA4D95LE-5 engine.

3.3 S4D95LWE-5 and 4D95LWE-5 engines

The S4D95LWE-5 and 4D95LWE-5 engines are swirl current chamber system (IDI) engines that cover the output ranges of 48 to 55kW and 40 to 48kW, respectively. The IDI engine has two combustion chambers, namely, a sub-chamber called a swirl chamber and a main chamber. The generation of NOx is controlled by low-temperature combustion in the sub-chamber and the combustion gas emitted by the sub-chamber is again combusted in the main chamber, to curb the generation of PM. **Figure 8** shows an appearance of the 4D95LWE-5 engine. The technologies incorporated in this engine are described below.

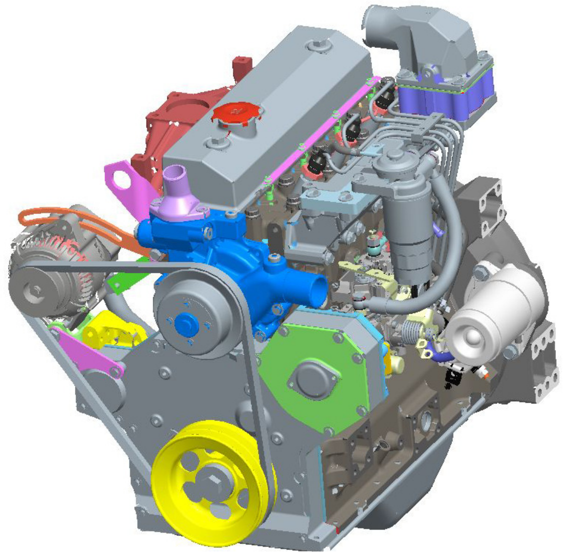

Fig. 8 Appearance of 4D95LWE-5 engine

3.3.1 Combustion chamber for IDI (Indirect injection)

The cross section of the combustion chamber for the IDI engine is illustrated in **Figure 9**.

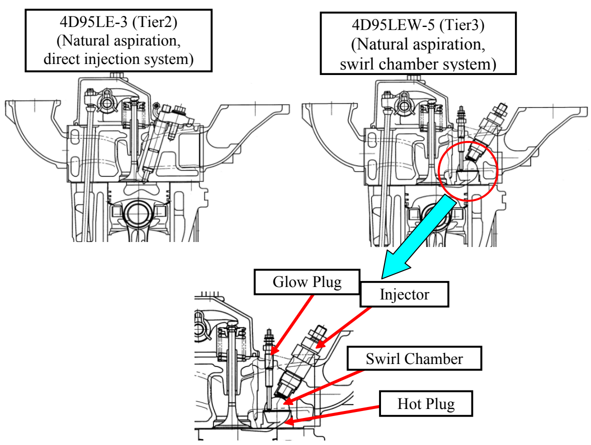

Fig. 9 Cross section of combustion chamber for IDI engine

The combustion of the IDI engine consists of the following two combustion modes. The first combustion mode is primary combustion caused by mixing of a tumble current (vertical swirl) that is generated when air in the cylinder is fed to the sub-chamber during the compression process and fuel injected by the injector. The second combustion mode is secondary combustion in the main chamber when the combustion gas in the sub-chamber is injected from the throat part of the hot plug as the piston lowers.

The S4D95LWE-5 and 4D95LWE-5 engines improved combustion to be compliant with the Tier3 exhaust gas regulation by tuning the shape of the throat part (combustion gas outflow part) of the part that constitutes the sub-chamber called a hot plug and shape of the piston combustion chamber. More specifically, the foregoing shapes were 3D modeled and flows of air and combustion gas were simulated. **Figure 10** shows part of the simulation results.

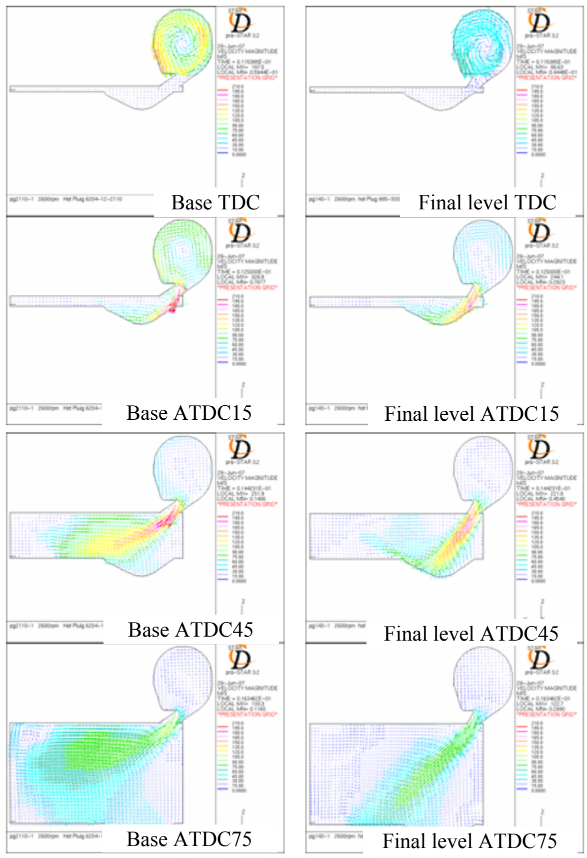

Fig. 10 Simulation results of air and combustion gas

A NOx reduction was forecasted by reducing the tumble current (vertical swirl) of air generated in the sub-chamber to curb the mixture of a fuel and air as the simulation result of the final level shows. A reduction in black smoke and PM emission was forecasted possible by optimizing the throat shape to increase the combustion gas injection speed from the sub-chamber and to increase the air utilization factor in second diffusion combustion. A design was made based on this simulation and emission performance was improved as shown in **Figure 11**.

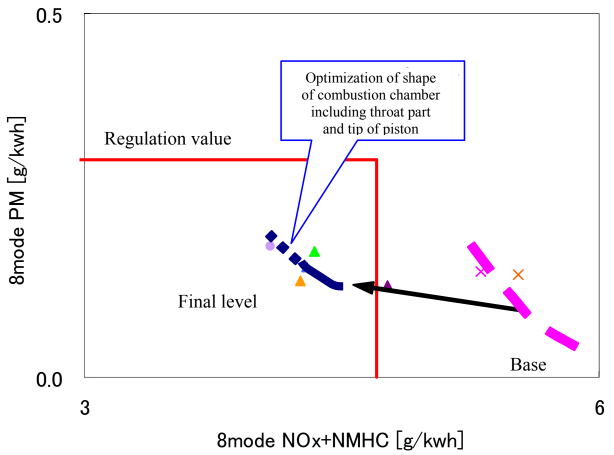

Fig. 11 Emission performance of 4D95LE-5 engine

3.3.2 Characteristics of mechanical fuel injection pump for IDI engine

1) 2-stage cam shaft

Figure 12 compares fuel feed ratios of mechanical fuel injection pumps. The fuel feed ratio reaches maximum on the start of fuel compression with ordinary fuel injection pumps, whereas the fuel injection pump for IDI curbs the fuel feed ratio on the start of fuel compression through a 2-stage cam. This controls radical mixing of a fuel and air in the initial stage to curb the combustion temperature and to reduce NOx emissions. The fuel feed ratio is increased in the second half of the combustion to increase the flow rate of the combustion gas that is jetted from the sub-chamber to the main chamber. This accelerates the second-half diffusion combustion and reduces the emission of black smoke and PM.

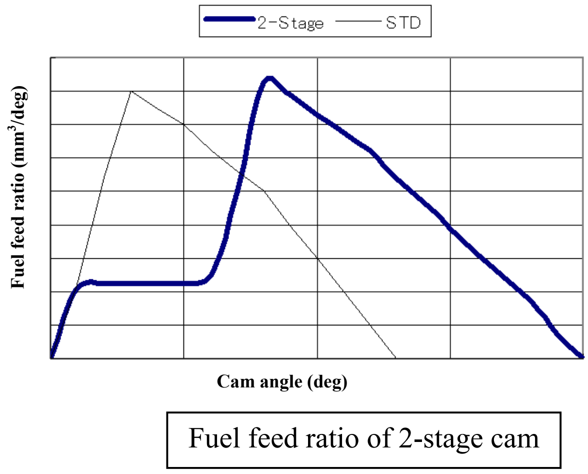

Fig. 12 Fuel feed ratios of fuel injection pumps

2) CSD (Cold start device) - Starting timing control device

When the injection time is delayed to reduce NOx emissions, the spark advance quantity necessary for starting at a low temperature and for the control of white smoke cannot be achieved with mechanical fuel injection pumps whose degree of freedom of injection timing is low. This problem was solved by installing a device (cold start device [CSD]), which advances the injection timing only when the temperature is low, on the fuel injection pump. An appearance of this device is shown in **Figure 13**. The CSD advances the injection timing at a low temperature by linking the piston that is sealed with wax, which expands or contracts depending on the cooling water temperature, and timing control device of the injection pump. The injection timing could be advanced a maximum 10° CA at a low temperature, accomplishing a good startability and reduction in white smoke also.

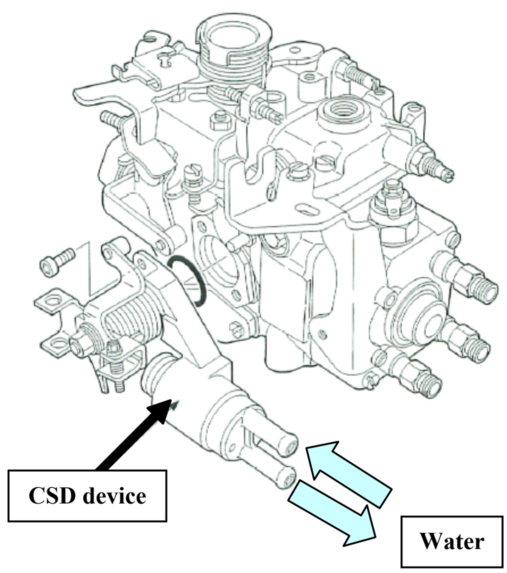

Fig. 13 Full view of CSD

3.3.2 Performance of 4D95LWE-5 engine

1) Emission performance

A regulation value in Option1 (Opt1) or in Option2 (Opt2) can be selected for the output range of 37kW to 56kW in US EPA Tier3 regulation. **Table 2** shows the regulation values and starting years for Tentative Tier4.

Table 2 US EPA regulation values (37kW to 56kW)

EPA Tier3 regulation EPA	Regulation value (g/kWh)		Starting year for Tentative Tier4
	NOx+NMHC	PM	
Opt.1	4.7	0.3	2013
Opt.2	4.7	0.4	2012

The selection of Opt1 offers the following advantages.

- The starting year for Tentative Tier4 for European EU regulation and US EPA regulation will be the same, 2013, and engines complying with these regulations can be introduced at the same time.
- Tentative Tier4 may require an after treatment device such as DPF and a cost increase due to installation of such device will be unavoidable. However, economical Tier3-compatible engines can be supplied one year longer.

Taking these advantages into consideration, Opt1 was selected for the 4D95LWE-5 and S4D95LWE-5 engines that cover this output range and the engines complied with these regulations. As a representative, the emission performance of 4D95WE-5 is shown in **Figure 14**.

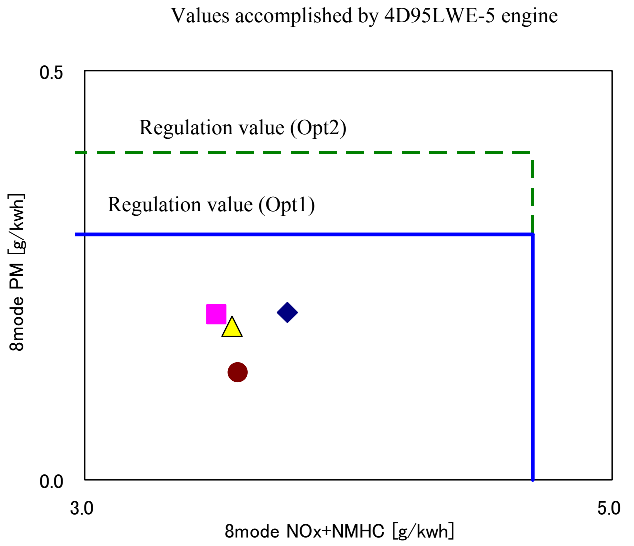

Fig. 14 Emission performance of 4D95LWE-5 engine

2) Engine noise performance

Figure 15 plots noise performance of the 4D95LWE-5 engine as a representative. The 4D95LE-5 engine lowered noise by about 3 or 4dB (A) in all operating speed ranges compared with engines of the direct injection type that complies with the Tier2 exhaust gas regulation.

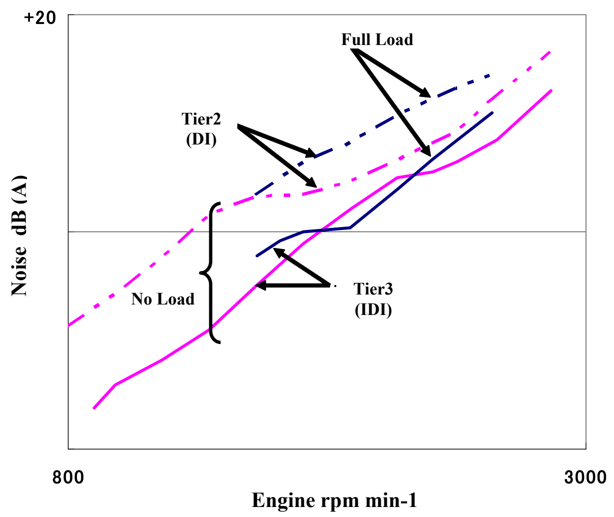

Fig. 15 Noise performance of 4D95LWE-5 engine

7. Conclusion

The features and emission reduction technologies of the 4D95 engine series, which is the anchor of the Komatsu ecot3 engine series are described. Among the accomplishments of this development is the new development of a specification incorporating an air-cooled aftercooler and common rail system. The potentials of the common rail system are very high. The SAA4D95LE-5 engine demonstrated excellent performance while complying with the Tier3 exhaust gas regulation, accomplishing a high output of 82kW in rated output also. The question is can the same means be applied to the 4D95LWE-5 engines (natural aspiration) of 48kW in rated output? The answer is no. A balance between "cost" and "means to comply with the exhaust gas regulation commensurate with the output" is difficult to achieve in design to comply with the exhaust gas regulation for small engines. A high output specification allows setting of a price commensurate with high performance by supplying high performance even if state-of-the-art technology of high functions is incorporated. When this principle is applied to engines of low output, the price per output significantly increases and engines will no longer be competitive in the market. The development of the 4D95 engine series complying with the Tier3 exhaust gas regulation has been accomplished by setting three aspirations, namely, TAA, T and NA, and two fuel injection systems, namely, the common rail system and a mechanical fuel injection pump. In a nutshell, the "4D95 engine series" could be realized by the development of indeed four different engines.

The emission regulation will continue to become stricter. Two questions for small engines will be the "keys to survival." How to "neutralize" cost increases that will be necessitated when EGR, DPF and other emission reduction technologies that are still high priced are incorporated to comply with stricter regulation and how technologies to reduce emissions to cover low output ranges in the same engine series can be made simple and low cost?

Reference:

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Introduction of the writers

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[A few words from the authors]

The development of engines to comply with the Tier3 exhaust gas regulation has been completed and the future task will be to develop engines that will comply with the Tier4 regulation. As mentioned above, complying with the Tier4 regulation may require the installation of devices such as EGR and DPF. Efforts will continually be made to develop and sell engines that will be competitive in all aspects by modifying the basic performance of the engine body so that the installation of these additional devices will not impair the characteristics requirements demanded for small diesel engines such as compactness and cost competitiveness.