Technical Paper

# Development of Tier3 Engine ecot3

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*The ecot3 engines were developed to meet the Tier3 emission regulations and introduced into the market as Komatsu engine series. The new technology and components were developed and built in to overcome the more hard emission regulation and noise requirement, keeping the better performance, reliability and durability than the current engines. The background of the development and technical features are described below.*

***Key Words:*** *diesel engine, environmental friendliness, Tier 3, electronic control, common rail system, EGR system*

## 1. Introduction

Because of their high fuel versatility and high efficiency, diesel engines are used in a wide range of industries as motive power sources. On the other hand, their impact on the environment and organisms has been pointed out, and the situation surrounding diesel engines is approaching a major turning point.

Against this backdrop, exhausted gas regulations are being tightened throughout the world year after year on diesel engines, also for the construction machinery. Regulatory levels centering on the U.S.A., Europe and Japan as three poles in particular are leading the trend for exhausted gas regulations on diesel engines for the construction and mining equipment.

Komatsu has developed and put on the market the “ecot3” (ecology & economy - technology3) engine series that meets the Tier 3 exhausted gas regulations of the U.S.A. EPA and European EU that were enforced in January 2006 and a system for the designation of construction machinery and the on-/off-road Tier 3 exhausted gas regulation in Japan scheduled to be enforced in October 2006. The engine has already been put into operation in the construction equipment and mining markets. This report overviews the Komatsu ecot3 medium/large engines that meet Tier 3 exhausted gas regulation and their technical features.

## 2. Trends of Emission Regulations on Engines for Construction Machinery

As mentioned above, emission regulations on diesel engines for construction equipment are the so-called Tier 3 regulations in Europe and U.S.A. and the construction machinery designation system on-/off-road Tier 3 exhausted gas regulation in Japan.

Trends of exhausted emission regulations in the U. S. A., Europe and Japan summarizing year-on-year changes are presented in **Fig. 1**. **Fig. 2** plots NOx + NMHC and PM emissions on the axes of ordinates and abscissas as trends of the EPA regulations from Tier 1 to Tier 2, Tier 3 and Tier 4 as a typical example. Macroscopically, the regulatory phases become stricter every 3 to 5 years. The principal regulatory values on nitrogen oxides (NOx) and suspended particulate matter (PM) have been required to be reduced by about 30% in level. Comparing the regulatory level in 1996 and the EPA Tier 3 regulation enforced in 2006 spanning a period of about ten years, exhausted gas emissions have been reduced to about 1/3 and will be reduced to about 1/20 in a span of about 20 years when the Tier 4 regulation is enforced.

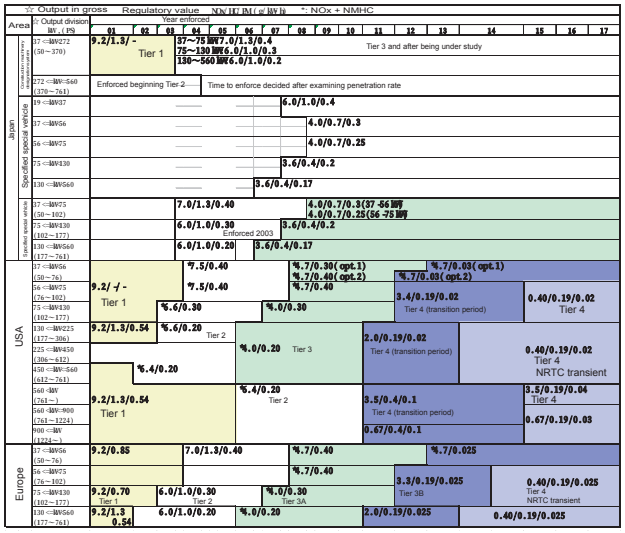
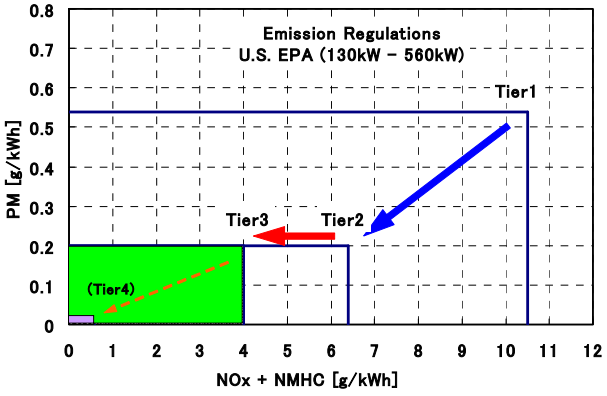



**Fig. 1** Worldwide emission legislation




(NOx and HC are regulated individually in Tier 1 and Tier 4. The values in the diagram show values added.)

**Fig. 2** History of NOx and PM emission levels

## 3. Development of ecot3 Engine Series

### 3.1 Outline of ecot3 Engine

Komatsu is currently developing, manufacturing and selling industrial diesel engines ranging from 3.3 L to 78 L. As mentioned above, new exhaust gas regulations have been and will be enforced in the U. S. A., Europe and Japan in 2006 and 2007. The medium to large ecot3 engine series ranging from 11.0 L to 23.2 L is described below as part of the series that ranges from 3.3 L to 23.2 L developed tuned to the enforcement of these regulations and complying with the Tier 3 exhaust gas regulations on 560 kW and below.

**Fig. 3** plots the displacement and output of the ecot3 engine series.

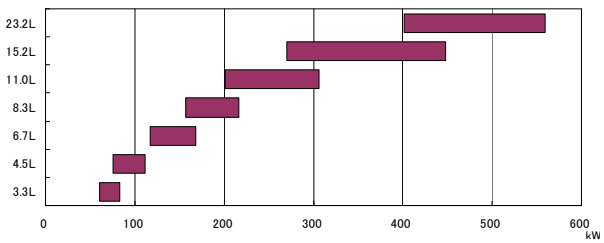



**Fig. 3** Komatsu ecot3 engine series

An overview of the technical trends incorporated in the engine series to meet the exhaust gas emission regulations is outlined in **Fig. 4**.

The combustion temperature inside the cylinders needs to be lowered to curb the oxidation of nitrogen to reduce the nitrogen oxides (NOx). As a means to accomplish this, the engine has undergone changes from being a super charging engine (S) to an engine with a water-cooled aftercooler (SA), and an air-to-air air-cooled aftercooler (SAA). Almost all engines in the ecot3 engine series have an air-cooled aftercooler. The nitrogen oxides have been further reduced, by technology to improve combustion through multi-injection and optimizing the injection timing, and by adopting cooled exhaust gas recirculation (EGR). The suspended particulate matter (PM) have been reduced by shortening the injection duration, by making the particle size of injection particles finer and by improving combustion through electronic controlled, a high-pressure injection system and an improved injector nozzle.

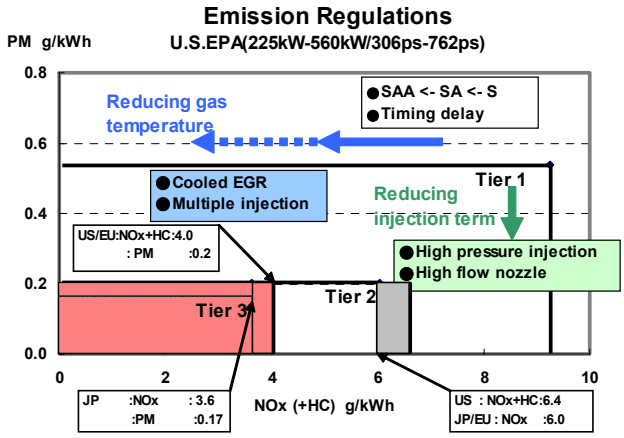



**Fig. 4** Technologies incorporated for emission reduction

### 3.2 Objectives for Development of the ecot3 Engine Series

1) Compliance with Tier 3 exhaust gas regulations of the U. S. A., Europe and Japan
2) Equal or higher engine performance (output and fuel consumption) compared with existing machines
3) Quietness to comply with the EU noise regulation on construction equipment
4) Reliability and durability as industrial engines for construction equipment and other machines

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Displacement | L | 3.3 | 4.5 | 6.7 | 8.3 | 11.0 | 15.2 | 23.2 |
| Bore | mm | 95 | 107 | 107 | 114 | 125 | 140 | 170 |
| Emission level | | Tier3 | | | | | | |
| Fuel Injection System | | New Heavy Duty Common Rail | | | | | | |
| Engine control | | Electronic | | | | | | |
| EGR | | None | | | | Cooled EGR System | | |
| Emission level | | Tier2 | | | | | | |
| Fuel Injection System | | Conventional mechanical pump | | | | Common Rail | | EUI |
| Engine control | | Mechanical | | | | Electronic | | |
| EGR | | None | | | | | | |

**Fig. 5** Principal technologies incorporated in the ecot3 engine series

To accomplish these development objectives, as shown in **Fig. 5**, the medium to large ecot3 engine ranging 11.0L to 23.2L equips the next-generation electrically controlled

high-pressure common rail injection system and the newly developed electrically controlled cooled EGR system. **Fig. 6** shows the view of a medium 15.2-L engine.

**Fig. 6** SAA6D140E-5 engine in the ecot3 series

## 4. The ecot3 Engine Technology

The ecot3 engine technology has been a key technology for the engine to comply with Tier 3 emission regulations and to meet the latest worldwide exhaust gas emission regulations, at the same time ensuring equal or higher engine performance (output and fuel consumption) compared with existing machines, which is a development objective as mentioned above. The newly developed ecot3 technology is described below.

### 4.1 Electronic Control System

The new ecot3 engine series equips the electronically controlled common rail injection system as a full-line electronic control system.

The electronic control system equips an entirely new ECM, which has been developed to upgrade a memory capacity about 10 times and more pins of about 1.5 times those of the conventional ECM, to meet higher engine performance. The total vehicle control technology of Komatsu as a leader in construction equipment and industrial machines has been fully utilized in developing the electronic control system.

This has enabled the development of ECM hardware and software common to small and large engines. Enhanced common design among engines and among vehicle application series has assured the provisioning of more uniform interfaces to users. The common design has also been verified by quality checks totaling 100,000 hours to ensure durability and reliability to fully meet customer expectations under various environmental conditions and in various usages.

In functions, control of confounding with VCM (vehicle computer) is conducted by high-speed CAN communications in conjunction with engine control including control of the common rail injection system and EGR system. Interfaces that can be connected to the KOMTRAX system are also provided.

Torque-based control is adopted in engine control to ease confounding control with the vehicle, and the development time has been shortened by changing the software to model-based software using Matlab/Simulink.

### 4.2 Heavy-duty Common Rail Injection System

The ecot3 engine series equips the electronically controlled common rail injection system in its entire engine models.

The common rail injection system allows not only high-pressure injection, but also a high flexibility of injection timing and multi-injection, offering the highest potentials among various injection systems. From early on, Komatsu has been equipping the common rail injection system in its high-speed diesel engines for the construction equipment. Making further improvements based on reliability and durability that have been achieved, the series features a system with a maximum injection pressure of 160 MPa.

**Fig. 7** shows the newly adopted heavy-duty common rail system. **Fig. 8** shows performance improvement obtained by applying multi-injection using the common rail injection system. Multi-injection has improved fuel consumption by about 2% without deteriorating the PM level, while the NOx level is unchanged.

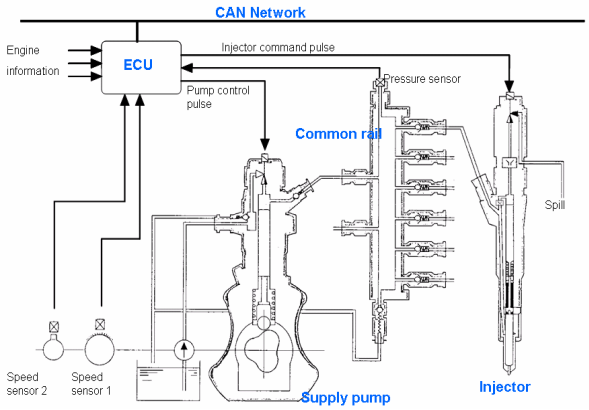



Fig. 7 Heavy-duty common rail fuel injection system

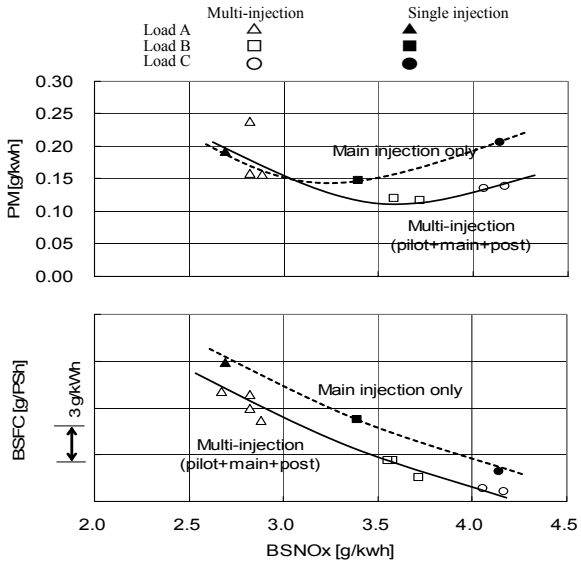



**Fig. 8** Performance improvement by multi-injection (SAA6D140E-5)

In incorporating the common rail injection system into the entire engine series, quality verification was performed with various test codes required for construction equipment fully utilizing the experience gained and technology used with Tier 2 emission engines. Improvements have been made in minute detail to perfect a system that can be called a heavy-duty specification.

### 4.3 ecot3 Combustion System

High priority was given to the development of a combustion system in developing the new engine that meets Tier 3 exhaust gas regulations. The EGR technology widely used in truck engines and other engines reduces emissions and is a very effective technology for emission reduction as well as for fuel economy. On the other hand, cost increases for EGR coolers and valves and other parts for this technology are a negative factor, especially for small engines.

As mentioned above, small engines in the ecot3 engine series adopt a new combustion system for high performance and compliance with emission regulations by upgrading the injection performance through the electronic control common rail and through the development of combustion technology while maintaining cost competitiveness. Medium to large engines, with which fuel consumption is a very important factor, are installed with an EGR system, which is described in the following, to feature low fuel consumption as a marketing strategy over competing machines.

The basic concept of the new combustion system reduces NOx by curbing the development of flames in the early stage of combustion as plotted in the heat release pattern inside the cylinder shown in **Fig. 9** to control the rise of the maximum temperature inside the cylinders. Instead, diffusion combustion in the final stage of combustion is activated to reduce PM, and high engine performance is accomplished by significantly reducing the combustion duration. In this tuning, 3D simulation was used to efficiently design the combustion chamber shape and injector specification (**Fig. 10**).

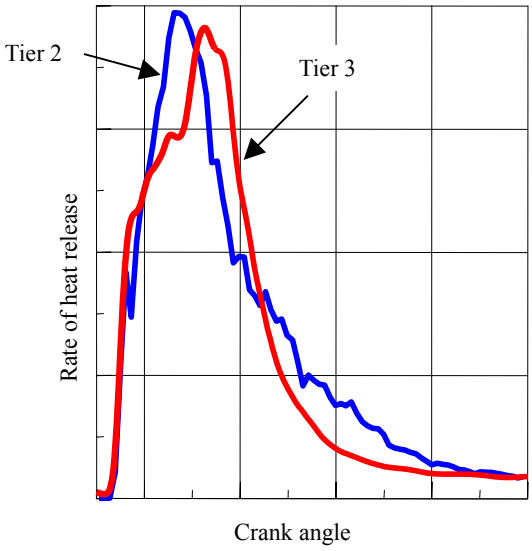



**Fig. 9** Concept of the new combustion system

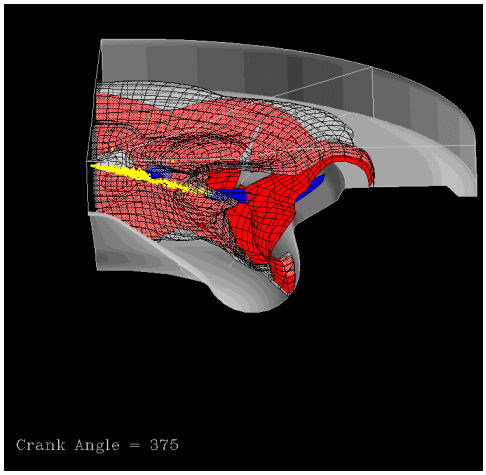



**Fig. 10** Example of 3D simulation for design of combustion parameters

A good balance between emission reduction and low fuel consumption, which are incompatible elements, is achieved by effectively utilizing the multi-injection shown in **Fig. 11** as the basic concept of injection as against the basic concept of combustion. As shown in **Fig. 12**, the performance of the Tier 3 SAA6D140E-5 engine that has been achieved is satisfactorily low in NOx and PM level compared with the Tier 3 emission regulation levels, while achieving lower fuel consumption over the Tier 2 engine.

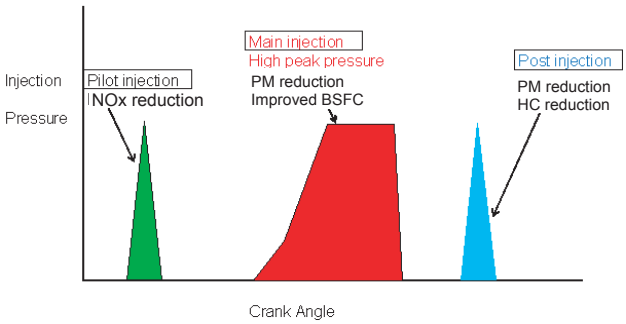



**Fig. 11** Typical injection control concept of the ecot3 engine

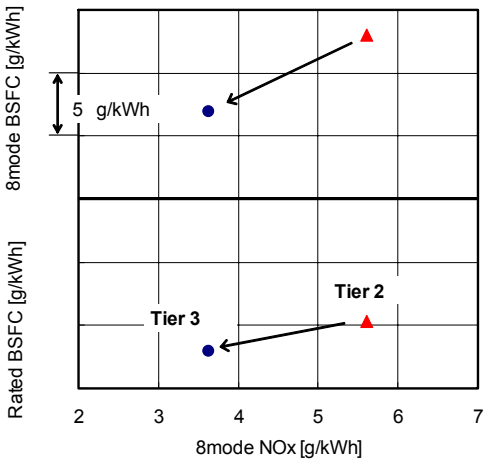



**Fig. 12** Example of performance change from Tier 2 to Tier 3 (SAA6D140E-5 engine with EGR, modified combustion, air-cooled aftercooler and heavy-duty common rail)

### 4.4 Turbocharger and Air-to-Air Charged Air Cooling System

Another important trend of emission control technologies of engines for construction equipment is the adoption of the air-to-air supercharging cooling technology that is also extensively adopted in truck engines. This technology is intended to increase the mass flow of air that is suctioned into the power cylinders of the engine and to lower the intake air temperature. **Fig. 13** shows an engine that is equipped in the hydraulic excavators of Komatsu. This system lowers the temperature of the hot air super charged by the turbocharger to the required temperature by a heat exchanger (air-to-air). The system achieves a low combustion temperature and low NOx.

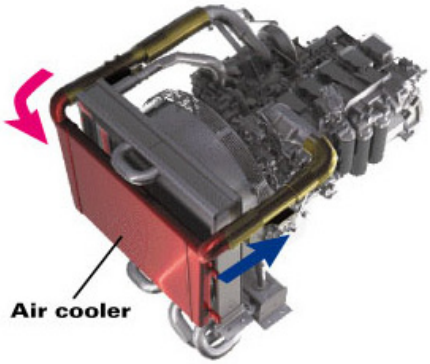



**Fig. 13** KOMATSU SAA6D140E-5

**Fig. 14** shows the visualized calculation results of the hydraulic excavator airflow using CFD for a forecast of efficiency of the air-to-air system. Unlike trucks that cool the engine by the ram effect, diesel engines for construction equipment involve both machine noise regulation and heat balance, making the study and verification of airflow a very important element.

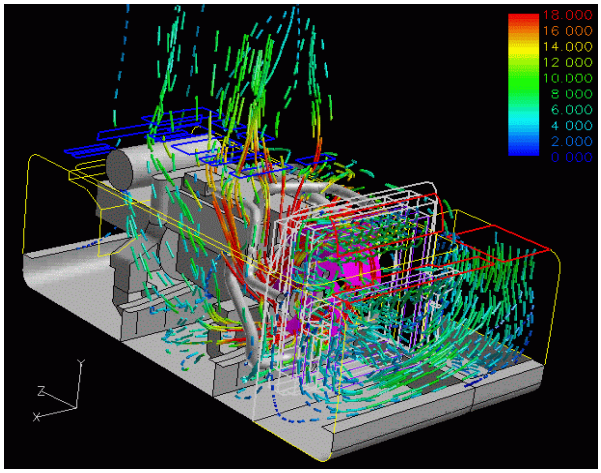



**Fig. 14** CFD model for airflow visualization

Komatsu has established viable reliable and durable technology in a severe condition over many years in its KTR turbocharger series that has been developed and manufactured by Komatsu. Recently, Komatsu has developed a turbocharger, KTR90, for medium engines, to expand the product lineup in the series (**Fig. 15**). A high-pressure ratio vs. high efficiency is achieved in Tier 3 by optimizing the compressor backward angle and inlet recirculation to achieve both high output and good combustion characteristics, also when EGR is installed.

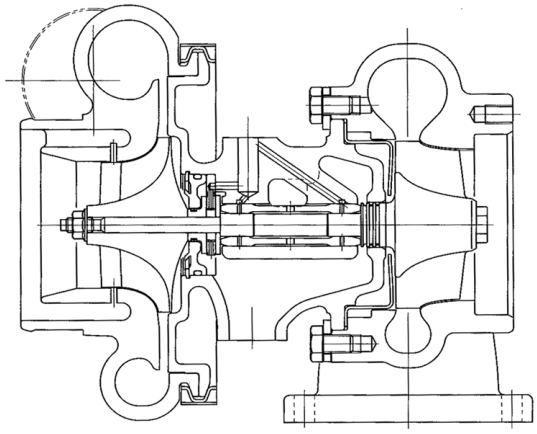


**Fig. 15** Newly developed KOMATSU KTR90 turbocharger

### 4.6 Twin-valve EGR System

A new cooled EGR system has been developed and equipped in medium to large engines 11.0 L or larger. **Fig. 16** shows the appearance of the 15.2L SAA6D140E-5 engine. In addition to the electronically controlled high-pressure common rail system mentioned above, a hydraulic drive electronic control cooled EGR system of Komatsu's unique twin-valve bypass assist type has been developed to meet the Tier 3 exhaust gas regulations and to obtain performance equal to or higher than that of existing machines.

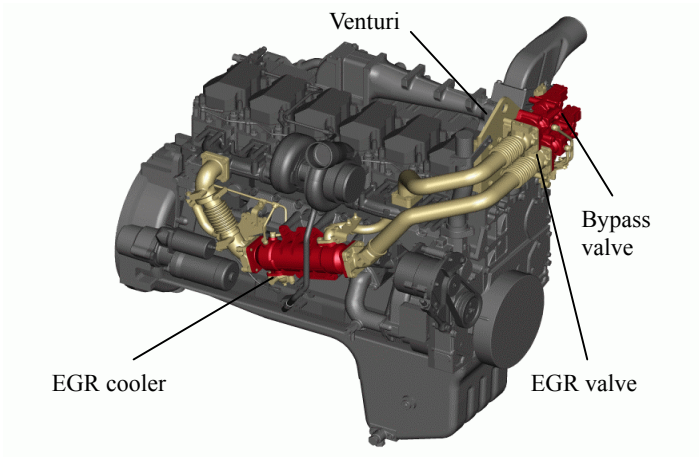



**Fig. 16** Appearance of SAA6D140E-5 engine

**Fig. 17** shows the configuration of the EGR system. A hydraulic drive electronic control valve uniquely developed by Komatsu is adopted as a twin-valve system consisting of an EGR valve and bypass valve and an optimal EGR rate to accomplish performance of high efficiency in the entire engine operating region from a low speed to the rated output point has been developed tuned to usage of construction equipment. A venturi mechanism is adopted to achieve a high EGR rate and uniform EGR gas. An example of fluid analysis conducted to optimize design of the venturi mechanism is shown in Fig. 18.

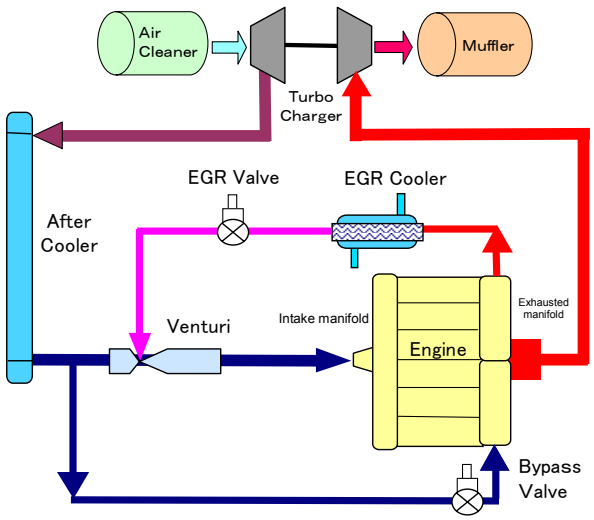



**Fig. 17** Twin-valve EGR system

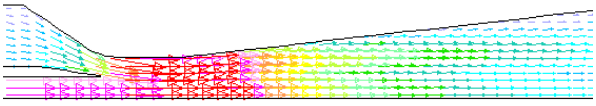


**Fig. 18** Example of fluid analysis for the venturi mechanism

## 5. Noise

In Europe, beginning 2006, the EU Stage 2 Noise Regulation will be enforced with construction equipment. For this reason, quietness of the engine body was an important development target in developing the new engine series.

Combustion noise of the engine has been reduced through pilot injection by the electronically controlled common rail system.

The efficiency of the vehicle cooling system has been enhanced by combining a large hybrid fan and hydraulic drive control, minimizing the total noise of the vehicle.

## 6. Reliability and Durability

In the development of the new ecot3 engine series, all Komatsu's quality verification codes for industrial engines that have been implemented in the past have been met. Additionally, new evaluation test codes have been developed and added to evaluate the new injection system and EGR system, and tests to adequately verify the reliability and durability of the new technologies have been conducted. Furthermore, to meet these test codes, the development activities included the development of a high-efficiency fuel filtration system, a special stainless steel EGR cooler that is fully durable against high-sulfur fuels (max. 5,000-ppm sulfur level for off-road vehicle fuels in North America in 2006) and the hydraulic drive electronic control EGR valve of Komatsu's unique design mentioned above.

As a result, the ecot3 engine series has demonstrated that it is fully reliable and durable in all severe environments and under all operating conditions expected for industrial engines in construction equipment and other machines.

Regarding main revolution systems such as the pistons, improvement has been made with the piston-cooling nozzles and piston rings to make these systems that have enjoyed a high reputation more reliable and durable. Higher durability could also be achieved in a scheme that combines EGR.

The cast iron monocoque piston (FCD piston) of Komatsu's unique design, which is one of the principal components, is shown in **Fig. 19**.

With the characteristic of high performance and high strength, new combustion system described above has been achieved without reducing the durability.

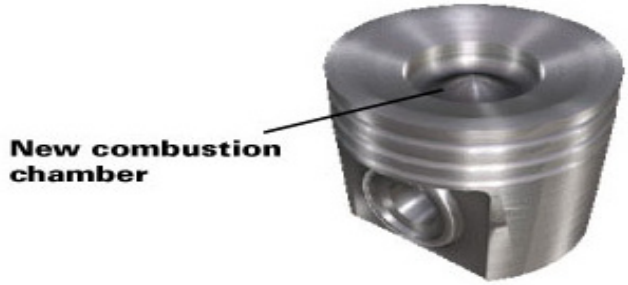



**Fig. 19** FCD piston and combustion chamber

## 7. Conclusion

The features and emission reduction technology of the newly developed ecot3 diesel engine series for construction equipment compliant to the Tier 3 regulations are described.

The emission reduction technology of diesel engines for construction equipment is entering an extremely important innovation period insofar as combustion improvement technology is concerned. In terms of the energy density and overall energy efficiency required for construction equipment, diesel engines will not soon be easily replaced by other motive power sources. However, one thing is certain at all times. It is most important not to forget the mission to continue minimizing impact on the global environment and to build machines that are better and higher in efficiency. In this sense, it is firmly believed that the development concept of this engine that always pursues low fuel

consumption matches the needs of society and gains the satisfaction of the customers in their use.

It has been about one year since it was introduced to its market, and we expect to start getting the various evaluation results of market. While paying attention to such information in market, we would be ready to respond as quickly as possible by means of “Reporting, Contacting, Consulting” when problems occur.

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State-of-the-art technology of “Komatsu ecot3 engine”

**Introduction of the writer**

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**[A few words from the writer]**

It is important to continue working on the technology to comply with exhaust gas regulations for diesel engine. By using the accumulated knowledge to comply with “Tier1 to Tier2 to Tier3,” the writers would like to keep on challenging to comply with Tier4, which is much higher hurdle.