

Simultaneous Improvement of Fuel Consumption and Exhaust Emissions on a Multi-Cylinder Camless Engine

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Ryo Kitabatake, Akihiko Minato, Naoki Inukai and Naoki Shimazaki
Isuzu Advanced Engineering Center, Ltd.

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ABSTRACT

Further improvement in fuel consumption is needed for diesel engines to address regulatory requirement particularly for heavy duty diesel in Japan enforced in 2015, in addition to the compliance to the regulatory requirements for exhaust emission, which seems to be more stringent in future. The authors have participated in the project of “Comprehensive Technological Development of Innovative, Next-Generation, Low-Pollution Vehicles” organized by New Energy and Industrial Technology Development Organization (NEDO), and innovative devices such as multi stage boosting system, ultra high-pressure fuel injection system and variable valve actuation (camless) system had been developed in this project from a standpoint of simultaneous improvement of fuel consumption and exhaust emission.

In camless system, intake and exhaust valves are driven by hydraulic pressure. So, fully flexible setting of opening and closure timings and lift of the intake and exhaust valves is possible. In this paper, steady-state operation test was conducted by adopting a combustion chamber with geometric compression ratio of 20.0 and an Electro-Hydraulic Camless System in the multi-cylinder engine with 3 stage turbo charge system. The engine performance and exhaust emissions were compared to same base engine equipped with 3 stage turbo system, piston of geometric compression ratio of 16.2 and cam drive valve train.

As a result of steady-state operation test, potential of improvement of fuel economy was indicated in this engine system. In addition, due to cylinder deactivation operation, further improvement of fuel economy was achieved in extremely low load range by reduction of heat loss. With

regard to the BSFC based on JE05 mode -converted value with giving consideration to the result of cylinder deactivation operation, improvement of 8.9% was obtained.

With regard to the early exhaust valve opening (EEVO) for which effect to improve turbo charger response is expected as well as the negative valve overlap (NVO) for which making up for delay of external Exhaust Gas Recirculation (EGR) by internal EGR, the operation for 70 seconds was extracted from JE05 mode operation to implement partially transient operation on trial basis. It was confirmed that both EEVO and NVO were feasible by using this camless system.

Further simultaneous reduction of both fuel consumption and exhaust emission in JE05 mode operation is expected by controlling intake and exhaust valve lift with giving consideration to the effect of external disturbance, improved thermal efficiency by increase of expansion ratio, implementation of each cylinder control for each load range including the switching control to cylinder deactivation operation, and suppression of spike-like NOx and soot emissions by adopting EEVO and NVO.

INTRODUCTION

Further improvement in fuel consumption is needed for diesel engines to address regulatory requirement particularly for heavy duty diesel in Japan enforced in 2015, in addition to the adaptation to the future exhaust emission regulation which is more stringent. From fiscal year 2004 to 2008, authors have participated in the project of “Comprehensive Technological Development of Innovative, Next-Generation, Low-Pollution Vehicles” organized by New Energy and Industrial Technology Development Organization (NEDO) [1]. The development targets of this program were as below:

NOx: 0.2 g/kWh, PM: 0.01 g/kWh in JE05 mode operation which is exhaust emission test mode in Japan. Further, improvement of fuel consumption of 10% versus current level is required. These levels are more stringent even in comparison with post new long-term regulation in Japan. To achieve the above target, it is necessary to achieve simultaneous improvement of both exhaust emission and fuel consumption. Particularly, the improvement of tradeoff between NOx and fuel consumption is imperative.

According to the report by Nitta et al., the above-cited targets can be achieved by combined use of sequential 3 stage turbo charge system (3st system) and exhaust after-treatment system [2]. In this study, emphasis of development is placed on the Variable Valve Actuation System as a basis for further improvement of fuel consumption by using a concept of future diesel engine indicated in the next chapter.

In the Variable Valve Actuation System for the diesel engine, various structures have been proposed and studied depending on the scope of control [3,4,5,6,7]. As the Variable Valve Actuation System for the this study, proprietary Electro-Hydraulic Variable Valve Actuation (Camless) System that uses hydraulic pressure for controlling opening and closing operation of intake and exhaust valves was used [8]. In this report, the impacts on the fuel consumption and exhaust emission will be discussed, when adopting camless system and geometric high compression ratio piston for the multi-cylinder engine with the 3st system.

CONCEPT FOR FUTURE DIESEL ENGINE

To achieve simultaneous reduction of both fuel consumption and exhaust emission, a concept for future diesel engine as illustrated in [Figure 1](#) is proposed. To improve fuel consumption, achieving a closer approximation to constant volume combustion and increasing of expansion ratio are useful from the standpoint of thermal efficiency improvement based on cycle theory. While optimization of fuel injection timing and increase of fuel injection pressure may lead to improvement in degree of constant volume, it is concerned about increase of NOx emission due to rising of in-cylinder temperature. For this issue, adoption of multi stage boosting system is effective that is able to realize the sufficient amount of in-cylinder oxygen for injected fuel quantity while maintaining of low oxygen concentration of in-cylinder gas. Besides, the high turbo-charging using the multi-stage turbo charge system will contribute to further improvement of thermal efficiency by inhibiting drop of specific heat ratio of the in-cylinder gas.

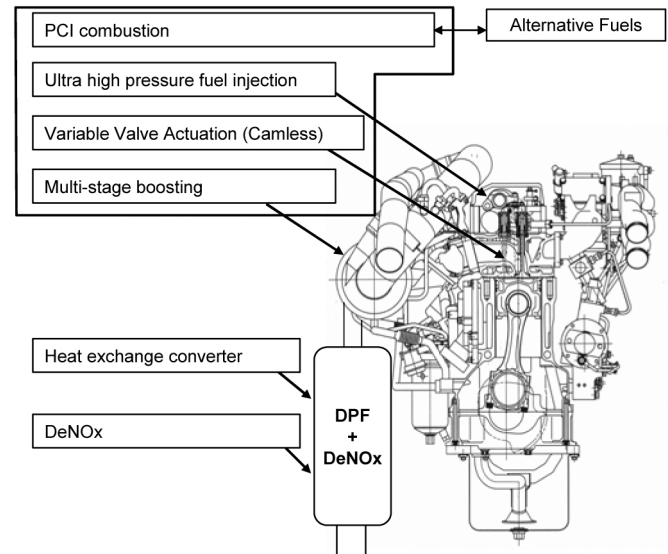


Figure 1. Future diesel engine concept for simultaneous improvement of exhaust emission and fuel consumption

Higher geometrical compression ratio was employed to increase expansion ratio. However, because the increasing of compression ratio and high turbo charging will accompany rising of maximum in-cylinder pressure (P_{max}), it is considered that the system may exceed the limit of P_{max} which is defined by mechanical strength of the engine, at the high load range. Therefore, adoption of Variable Valve Actuation System is proposed that maintains high expansion ratio and avoids excessive rising of P_{max} through controlling effective compression ratio based on variable setting of intake valve closure (IVC) timing.

Nevertheless, suppression of effective compression ratio in high load range leads to deterioration of volumetric efficiency, which is associated with the concern of soot emission increase. To address this issue, a micro-hole nozzle below $\phi 0.10\text{mm}$ diameter is arranged and ultra-high pressure fuel injection system up to 300MPa is used to suppress soot emission by promoting atomization of fuel spray and mixing of fuel and air [9].

With regard to the operation condition with improved fuel consumption through the use of the above-mentioned devices, drastic drop of exhaust gas temperature is feared. In such a case, there is a concern that NOx conversion rate will drop due to lower conversion efficiency of exhaust after-treatment system. Therefore, the developments of catalyst with higher conversion efficiency in low temperature range as well as heat exchange converter using heat release through catalyst reaction are promoted with the purpose to decrease exhaust emission at tail-pipe out [10].

Besides, in the low-load area where exhaust gas temperature is extremely low and it is difficult to purify NOx even when

using the heat exchange converter, adoption of low-NO_x combustion method such as Premixed Compression Ignition (PCI) combustion is considered effective. Therefore, investigation and proposal of optimal fuel property for low-NO_x combustion method and conventional diesel combustion method have been conducted [11].

EXPERIMENTAL RESULT AND DISCUSSION

EXPERIMENTAL SETUP AND PROCEDURE

Major specification of engine used for the test is shown in Table 1. The engine used for the test is the Inline 6 cylinder direct injection diesel engine with bore × stroke of $\phi 120.0\text{mm} \times 145.0\text{mm}$ and displacement of 9.84L. The 3st system is used for turbo charge system and the camless system is used for valve train. For combustion chamber, re-entrant type was adopted that has the geometric compression ratio of 20.0. As mentioned later, the operation condition which reaches P_{max} limit was not conducted in this study, the decreasing of volumetric efficiency due to suppression of effective compression ratio was avoided. For this reason, commercial production spec fuel injection system was adopted instead of the above-cited ultra-high pressure fuel injection system. With regard to the fuel, commercially available JIS #2 diesel fuel was used (this engine system is called “camless unit” hereafter). The schematic layout of 3st system and the overview of the engine system are shown in Figure 2 and 3, respectively.

Table 1. Engine specifications

Engine type	Inline 6 cylinder direct injection diesel engine
Bore	120.0 mm
Stroke	145.0 mm
Displacement	9.84 L
Boosting system	3 stage turbo charged
Valve train	Electro-hydraulic camless system
Swirl ratio	1.3 Ks
Fuel injection system	Common rail system
Nozzle type	$\phi 0.14 \times 8\text{holes}$, $\beta = 78^\circ$
Combustion chamber	Reentrant
Compression ratio	20.0:1
Fuel	JIS #2 diesel fuel

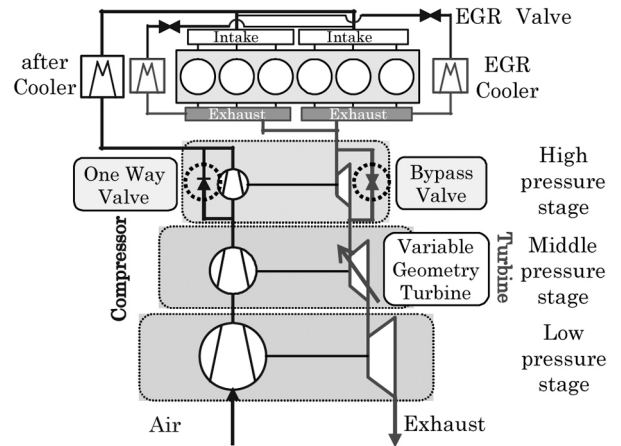


Figure 2. Schematic layout of 3 stage turbo charged system

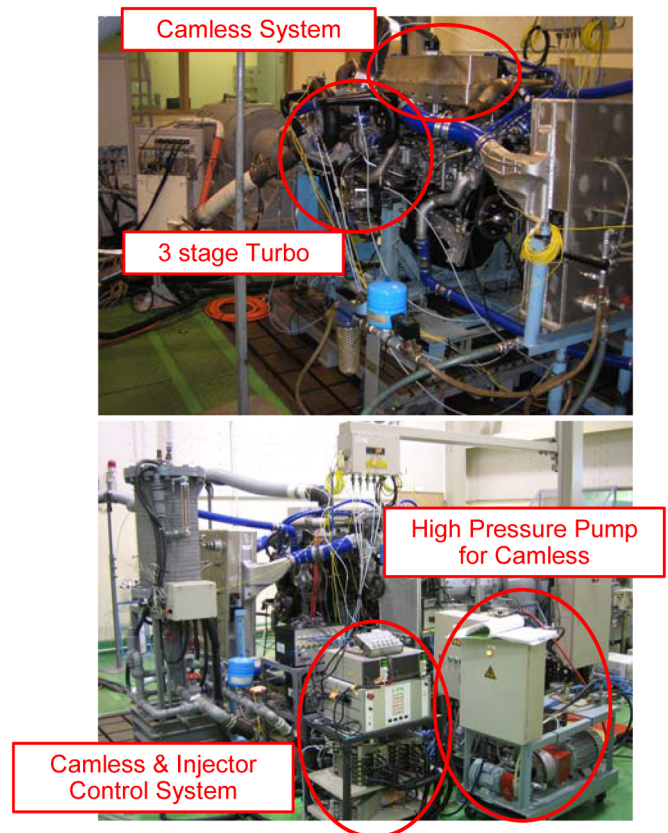


Figure 3. Appearance of 3 stage turbo charged and camless engine

In the camless system used for this test, intake and exhaust valves are driven by hydraulic pressure instead of using conventional cam shaft drive. In this system, fully flexible setting of opening and closure timings and lift of the intake and exhaust valves is possible by changing the charge and discharge timings of hydraulic pressure and input hydraulic energy. As an example of intake and exhaust valves drive using this camless system, valve motion indicating the