

Advanced Marine Engine which Reduces Environmental Load “The Wärtsilä X-series” Featuring a Fusion of Advanced Electronic Control Technologies

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In diesel combustion, there is generally a trade-off between fuel consumption and NO_x emissions. With electronically controlled engines (cam-less engines) that employ a common rail fuel injection system, there is flexible control of fuel injection and exhaust valve timing in accordance with engine load. By optimizing the setting of parameters based on the result of various simulations and engine testing, low-NO_x, highly efficient combustion has been achieved, which makes a major contribution to reducing environmental load.

1. Introduction

The electronic control using the computer and common rail system for fuel injection are implemented as general technologies for automotive engines. The common rail is a fuel injection system for diesel engines that increases the fuel pressure using pumps and pre-accumulate the fuel in the common high pressure pipe (common rail), and injects the accumulated high pressure fuel into each cylinder at a required timing via electronically controlled valves. There were many technical issues to be solved for applying the common rail technology because the fuel injection quantity for large size two stroke marine engines is about 4 000 times as large as automotive engines and the high viscosity Heavy Fuel Oil (HFO) containing a large quantity of impurities is used.

A licenser for Diesel United Ltd. (DU), Winterthur Gas & Diesel Ltd. (Switzerland) — the former Wärtsilä Switzerland Ltd. has been working on an electronically controlled fuel injection system and has established the common rail technology for fuel injection system for large marine engines after repeated technical improvements. In addition, the control of exhaust valves and starting valves has been computerized as well, and the world's first RT-flex as a large size marine engine with an implemented common rail was launched in the market in 2001. Currently, the RT-flex engines and its subsequent engines Wärtsilä X series (W-X engines) are the only engines which realized the common rail technology that accepts and uses heavy fuel oil.

Recently, the environmental compatibility is requested for marine engines as well, and the stepwise reduction of emission rates for nitrogen oxide (NO_x), etc., is required in accordance with the international regulations. The first stage NO_x emission control of the International Maritime Organization (hereinafter called IMO) was enforced in 2000, and the secondary control was enforced in 2011, and it is requested to satisfy the third restriction from 2016. In addition, the cut down on fuel consumption rate that greatly influences the reduction of CO₂,

and the ship operating cost is requested as well.

In this document, the environmental load reduction technologies for large marine engines by means of electronically controlled common rails are described.

2. The features of common rail type electronically controlled engines

There were difficulties in flexible optimization of control of injection timing and injection pressure because the conventional cam driven plunger-type fuel pumps compressed the fuel by the upward motion of the plunger raised by the rotation of the cam.

On the other hand, the common rail type engines do not increase the pressure every time the fuel is injected, but instead, always sustain the internal pressure of the common rail and automatically open/close fuel valves for the desired duration for injection of fuel, and also permit the flexible setup for the filled and sustained fuel pressure in the common rail. **Figure 1** shows the common rail type fuel injection system.

2.1 Fuel injection pressure

The injection pressure for cam-type engines increases approximately in proportion to the square of the plunger rising

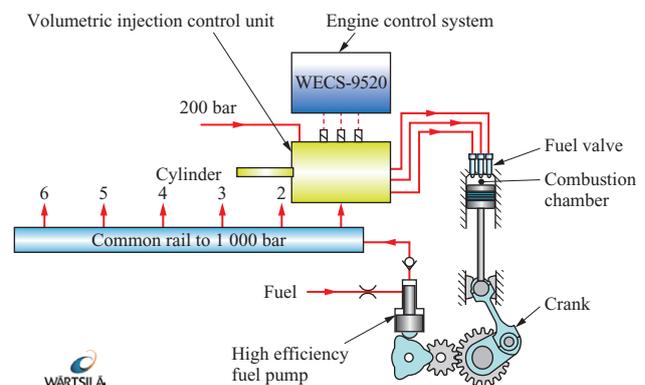


Fig. 1 Common-rail type fuel injection system

speed, and the plunger rising speed is determined by the cam rotational speed, and the cam rotational speed by the engine rotational speed; that provides the characteristics of low injection pressure in low speed range of an engine and the high injection pressure in the high speed range of an engine. Accordingly, it is difficult to control the fuel injection pressure independently from the rotational speed of the engine, and it has been a constraint on aiming at optimal tuning.

For a common rail type electronically controlled engine, the fuel injection pressure is controlled independently from the rotational speed or the load of an engine so that the optimal fuel injection pressure for variable loads of an engine is acquired. The fuel discharge rate of fuel supply pump that supplies the fuel to the common rail is controlled based on the pressure in the rail, while the discharge timing of the fuel pump is not related with the engine speed; the fuel pump for the RT-flex engine is driven at approximately 7-8 times as high a frequency as the rotational speed of an engine. Fuel pumps for conventional cam-type engines were implemented in every cylinder; on the other hand, the smallest number of fuel pumps for an RT-flex engine is only two.

In addition, the internal pressure of the plunger chamber was released at the end of injection for realizing a sharp cut off of fuel injection for cam-type engines, but to release the accumulated pressure meant a loss of energy and it resulted in low efficiency of the pumps. In addition to this, countermeasures were required for the pulses and cavitation erosions in the fuel oil return lines caused by this energy loss. On the other hand, the fuel pumps for the common rail is made by electronic control to discharge only the required quantity; which provides better efficiency and require no countermeasure for cavitation or pulses in the fuel return lines.

2.2 Fuel injection control

The RT-flex engine has optimum controls, in accordance with the engine speed and load, of ① injection timing, ② total injection quantity in one stroke, and ③ fuel injection quantity per unit time (hereinafter called injection rate) dependent on injection pressure. Among the above, the fuel injection controls except the injection rate ③ are realized by switching the servo oil path using a rail valve (high-speed electromagnetic valve) and driving the control valve in ICU (Injection Control Unit) in accordance with the command from the WECS (Wärtsilä Engine Control System). The fuel injection quantity in ③ sustains high latitude of control based on the control independent of the speed and load on the engine.

One of the reasons for difficulties with applying the common rail system to large marine engines was described above. The reason is the difficulty of direct use of fuel as servo oil because the fuel for large marine engines is heavy fuel oil with a variety of such characteristics as viscosity, heating value, and impurities for every bunker fuel. The ICU uses the lubricant oil with stable characteristics when pressurized and has an established function to properly control the fuel injection by switching the servo oil path with a rail valve and, at the same time, has a fail-safe function when a defect occurs in high-pressure pipes or fuel valves. This mechanism was the breakthrough for applying the common rail type fuel injection

system to the large marine engines that require high reliability.

Additionally, the delay in fuel injection has been improved by shifting some of the ICU functions to the fuel valves for W-X engines, the successor engines to the RT-flex engines. This will be described later.

2.3 High grade fuel injection control with common rail system

For RT-flex engines or W-X engines, various fuel injection patterns and parameters can be set up. The two typical fuel injection control patterns are explained here. All shown below are functions that belong only to the common rail-type engines that allow the separate control of multiple number of fuel valves implemented in the cylinder.

2.3.1 Reduction on the number of fuel injection nozzles

The duration of fuel valve open will be extremely short due to the decreased fuel injection quantity during low output operation. With conventional methods, the separate control of fuel valves were not possible because a fuel pump implemented in every cylinder operated multiple fuel valves at the same time and that made it difficult to acquire a good atomization of injected fuel oil. However, the number of operating valves for fuel injection can be reduced from the full number of equipped fuel valves in the case of an electronically controlled engine and can increase the fuel injection quantity per fuel valve so as to realize a good atomization with an extremely low output. As a result this has been achieved the stability of combustion. Additionally, an electronically controlled engine has a function to secure the uniformity of thermal load in a combustion chamber by sequentially using the injecting fuel valves after a certain fixed interval. **Figure 2** shows the restriction on the number of fuel injection nozzles for low loading.

2.3.2 Sequential injection

Figure 3 shows the sequential injection. This is a control method that makes the multiple fuel valves equipped in one cylinder inject with certain time differences. This aims at controlling the heat release rate, and the more precise heat release rate is realized by combining it with the above mentioned fuel injection pressure control.

The importance of controlling heat release is explained in **Chapter 3**.

2.4 Exhaust valve control

Figure 4 shows the exhaust valve control system. For RT-

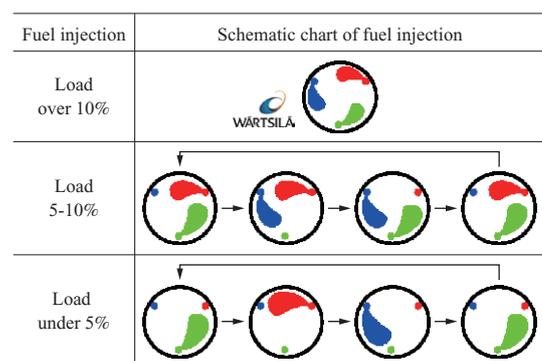


Fig. 2 Control of number of fuel injection nozzle used at low load

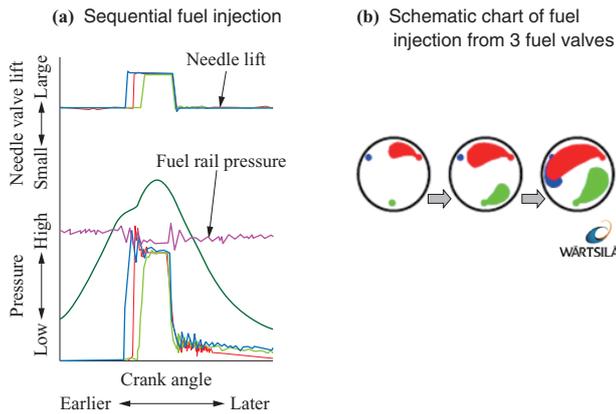


Fig. 3 Sequential injection

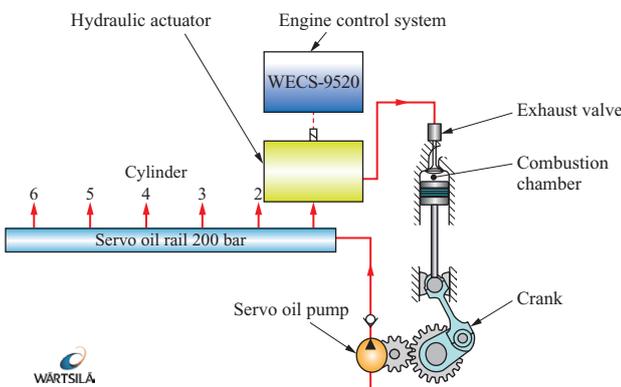


Fig. 4 Exhaust valve control system

flex and W-X engines, the common rail technology is applied to the exhaust valve control as well. Using lubricant oil for the engine as the servo oil, the oil pressurized by the servo pump driven through the crankshaft is accumulated in the servo oil rail. After that, the exhaust valve is opened by hydraulic pressure by switching the rail valve equipped in EVCU (Exhaust Valve Control Unit) in response to the command from the WECS similarly as fuel injection control. An air spring is implemented in the exhaust valve and closes the exhaust valve when the oil in the exhaust valve drive unit is pushed back by switching the rail valve.

For conventional cam driven exhaust valves, the flexible exhaust valve control compatible with the output or engine tuning methods was not possible because the exhaust valve actions were based on the cam profile. In addition, the cam profile had to be gently sloped due to the restrictions on the mechanisms of mechanical driving systems; as a result, the open/close of exhaust valve had a gentle curve that restricted the freedom of optimal exhaust control.

3. Flexible control based reduction of environmental load

3.1 Simultaneous reduction of fuel consumption rate and NO_x emission rate

For diesel engines generally, it is difficult to simultaneously reduce the fuel consumption rate and NO_x because these are the trade-off issues. The increased thermal efficiency will be

achievable with the tuning of combustion to complete while the volume of combustion chamber is small when the piston is near the Top Dead Center (TDC) for reducing the fuel consumption rate; however, the higher operating gas temperature in the combustion chamber will increase NO_x. This is due to the intense temperature dependence of generating speed of NO_x that is generated for the most part through the reaction of N₂ and O₂ in the atmosphere. For instance, if the duration of combustion is approximately 10 ms, the generated quantity of NO_x at flame temperature 2 400 K is 10 times as much as that generated at 2 200 K.

For this reason, it is required to realize good combustion with an inhibited rise in the combustion temperature through elaborate control for reducing the fuel consumption rate while reducing the NO_x emission rate. To realize this type of combustion, an excellent functionality of the common rail type electronically controlled engine is actively implemented for the RT-flex engines, and the effects brought about are described below.

3.2 The effect of sequential injection

The sequential fuel injection controls the amount of heat release per unit time (hereinafter called heat release rate) with the fuel injection rate control. The diesel engine adopts a form of combustion where the self-ignition of fuel takes place by fuel injection in the high temperature air filled in the cylinder and compressed by the piston. The high heat release rate will contribute to the increased flame temperature, and increase the generated quantity of NO_x as mentioned above. The higher heat release rate in the early stage of combustion is explained by the pre-mixing combustion due to the ignition delay, therefore the reduction in injection quantity in the early stage of fuel injection is effective for suppressing heat release in the early stage.

In the sequential injection, the staggered injection between multiple fuel valves could lower the injection rate in the earlier half of combustion without changing the total fuel injection quantity, and that could reduce the heat release rate in the early stage. **Figure 5** shows the comparison of heat

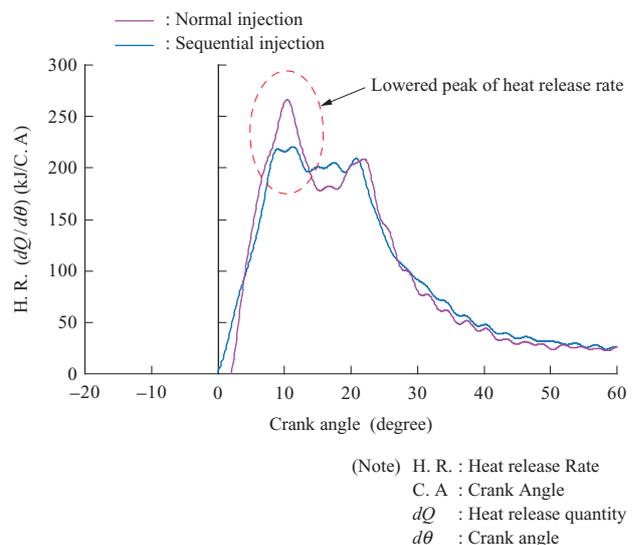


Fig. 5 Comparison of heat released

release rate between ordinary injection and sequential injection. The lowered peak for the heat release rate in the earlier half of combustion is observed when the sequential injection is applied.

For other electronically controlled engines, such as hydraulic cam-types, the fuel pumps implemented in each cylinder simultaneously operate the multiple fuel valves and that will not allow the individual control of fuel valves. From this restriction, the fuel injection rate is decreased by lowering the injection pressure in the earlier half of fuel injection aiming at the reduction of heat release rate in the earlier half of combustion. However, this method is not without a concern for bad influences on the combustion chamber components such as defective combustion and after burning due to insufficient atomization for large marine engines that use heavy fuel oil when poor quality fuel is bunkered.

3.3 The effect of exhaust valve control

The control of open/close timing for exhaust valves is effective for both lowering the combustion temperature and increasing the cycle efficiency. For diesel engines with combustion triggered by self-ignition in high temperature gas, it will be one of the measures for lowering the combustion temperature to aim at lower limit compression temperature required for self-ignition, while assuring the required quantity of air for combustion. Specifically, the set up to delay the closing timing of the exhaust valves as far as possible will be effective for lowering the pre-compression temperature and lowering the compressed air temperature dependent on the compression ratio. In addition, the delayed closing timing for exhaust valves will reduce the compression work of the piston. Furthermore, the cycle efficiency will be improved by prolonged expansion strokes due to the exhaust valve closing timing which is delayed as far as possible.

Such a cycle having low compression ratio/high expansion ratio with effective expansion stroke longer than the compression stroke is called a mirror cycle, known as an effective means for improving the cycle efficiency. **Figure 6** shows a comparison of exhaust valve control of cam-type engines and electronically controlled engines. It is recognizable that the electronically controlled engines flexibly vary the

closing timing of exhaust valves so as to provide an optimal control for different closing timing of exhaust valves in accordance with varying engine loads. It is also recognized that the flow coefficient of valve flow paths is improved by the better exhaust valve open/close response thanks to the exhaust valve open/close change curves more rectangular than those of conventional cam-type engines.

Further, it is important for aiming at an optimum tuning that a flexible controllability of exhaust valve open/close timing is achieved to bring out the potential of an engine to the best possible extent because the optimal open/close timings for exhaust valves are different from engine to engine in accordance with their specifications such as with or without exhaust waste gates for the charging system, etc.

In the above, for reducing the compression ratio as low as possible while securing the necessary amount of air for combustion, it is enough to increase the charging pressure (scavenging air pressure) for raising the air density. This pressure is largely dependent on the performance of charger and thereby the high compression ratio/high efficiency charger plays an extremely important role on reducing the environmental load caused by large marine engines.

A comparison of measurement results of cylinder internal pressure is shown in **Fig. 7**. The low-NO_x/high-efficiency combustion is realized by such a combustion method.

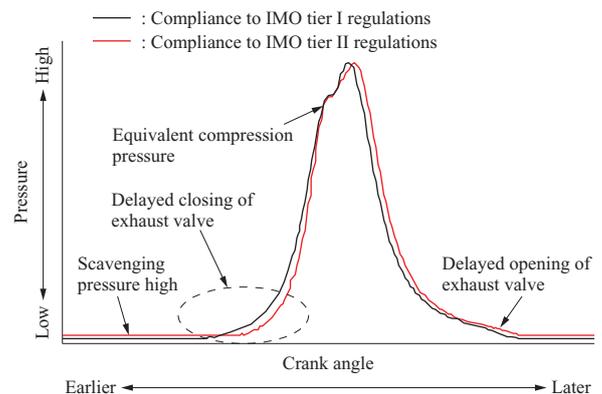


Fig. 7 Comparison of internal cylinder pressure

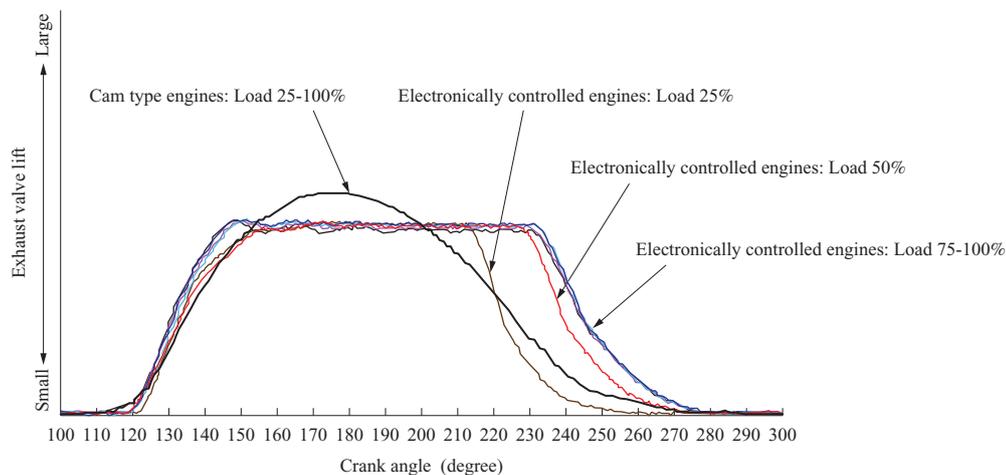


Fig. 6 Comparison of exhaust valve control

4. Evolution of common rail engines

As a subsequent engine type for RT-flex engines, the W-X series engines have been released aiming at the increased compatibility with hull and higher thermal efficiency. For these types of engines, the lower rotational engine speeds with the longer piston strokes, the latest fuel injection mechanisms and controlling system of RT-flex engines (common rail type electronically controlled engines) are implemented. As an example of the evolution and superiority of common rail type electronically controlled engines, the comparison by numerical simulations on the fuel injection behavior between the arrangements of injection control valves before high pressure fuel pipes (RT-flex engines) and after high pressure valves (W-X engines) is shown in Fig. 8 as part of the improvements of fuel injection mechanism.

When the injection control valves are arranged before fuel high-pressure pipes, the secondary injection takes place after completion of main injection (refer to Fig. 8 ①). The secondary injection is observed in a real engine depending on the conditions, and the reduction of fuel not contributing to the combustion supplied in the cylinders by the secondary injection will lead to inferior fuel consumption.

In addition, while the pattern of completion of injection is mild for the conventional types, the fuel injection valves arranged after fuel high pressure pipes sharply lower the

injection pressure, and at the same time, the injection completes earlier (refer to Fig. 8 ②). The mild lowering of injection pressure will deteriorate the combustion due to the fuel injection under low pressure; therefore, the improved combustion is expected by the arrangement of fuel control valves after fuel high-pressure pipes.

Further, the shortened delay of response from the command until the actual injection by the arrangement of injection control valves after high pressure pipes is also a great contributing factor for improved engine controllability (refer to Fig. 8 ③). Additionally, this delay in response is taken into consideration for the control of actual engines.

5. Conclusion

The DU-Wärtsilä large marine diesel engines have brought about the renewal of conventional common sense of control based on the rotation of cam shaft synchronized with the crank shaft and clearly shown its advantages of compatibility to the exhaust regulations and the higher efficiency over all the operational output range and were launched in the market as an environment friendly energy saving marine engines. Recently in the market for large marine engines, almost all of the contracted engines are proving to be electronically controlled engines for reduction of environmental loads, and the manufactured DU engines were already almost 100% electronically controlled since 2008. This is recognized as an effect of highly evaluated electronic control technology for common rail type RT-flex engines that feature the simple, flexible, and multi-functional solutions.

Not only the countermeasures for reducing the environmental load, but also the ease of continuous slow steaming operation seeking economic efficiency are achieved by the acquisition of various control flexibilities based on electronic control. Additionally, it greatly contributes to the improvement of automated troubleshooting supporting function based on feedback information from electronically controlled components, and it provides with other merits as well in addition to the performances of engines mentioned above.

Currently, the dual fuel engines that allow pre-mix combustion using the natural gas as a fuel as well as diesel combustion using heavy oil as fuel are being featured in the W-X engine series as well. For realizing dual fuel engines, these computer technologies are essential.

As explained, the common rail electronic control is a base technology for future development of large marine engines, and the simplicity of concept and high flexibility of control indicate a good possibility for further evolution.

Based on the fusion of large marine engines and electronic control technology reported in this document, efforts will be continued aiming at the simultaneous achievement of cut down of fuel consumption rate, reduction of NO_x emission, and the environmental load reducing technology in consideration of the flexibility in usability covering all the operational power ranges.

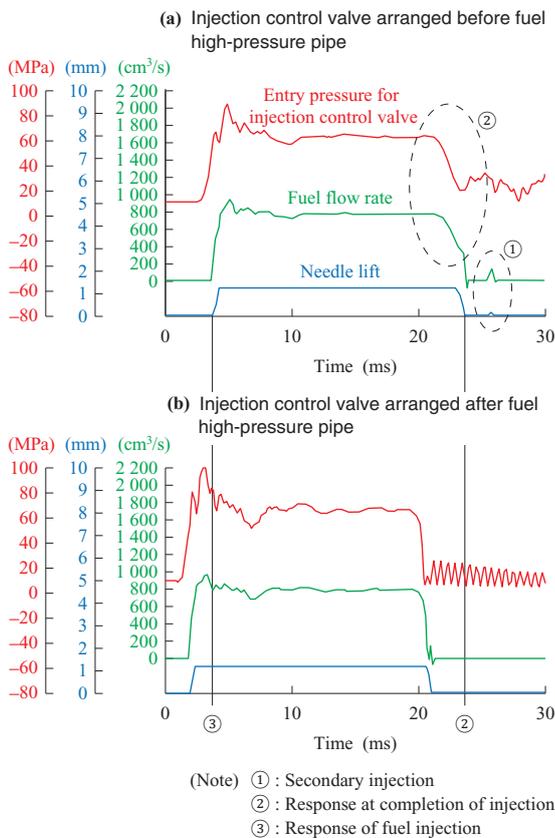


Fig. 8 Simulation comparing fuel oil injection