World's First Variable Compression Ratio System for Large Marine 2 Stroke Engines

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The Variable Compression Ratio (VCR) system for 2 stroke marine engines can reduce fuel consumption and adapt to various fuels. Therefore, this system is a very attractive device for achieving a sustainable society; and it also won the award for Marine Engineering of the Year 2018. This paper describes the overview of the VCR system, verification results of the VCR system and engine performance, and finally the impact of the VCR system on a sustainable society. The VCR system is currently under development and being targeted for early commercialization.

1. Introduction

In Japan, 99.7% (on a mass basis) of export and import cargo is transported by ship[(1)].Therefore large marine 2 stroke crosshead engines (large marine engines), which constitute a mainstream type of marine main engine, are essential industrial machinery in today's global society. Large marine engines have much higher thermal efficiency than automotive and other small engines, but in view of environmental burden — such as greenhouse gas emissions caused by the use of fossil fuels — and utilization of depletable resources, further improvements in thermal efficiency are expected in order to facilitate achievement of a recycling society that aims to be sustainable. In order to contribute to 3R (Reduce, Reuse, and Recycle), which is required in a sustainable society, large marine engines can reduce greenhouse gas emissions and fuel consumption (Reduce), convert to sustainable energy (Reuse), recirculate and reuse exhaust gases, and recycle engine parts (Recycle).

The International Maritime Organization (IMO) is strengthening marine exhaust gas emission regulations. For example, one IMO strategy is that, by 2050, total GHG (Greenhouse Gas) emissions from ships should be half that of the 2008 level. CO_2 accounts for most of greenhouse gas emissions, and CO_2 emissions from large marine engines can be reduced by converting to carbon-free fuels (e.g., NH_3, H_2) derived from renewable energy, biomass and other carbon neutral fuels, and LNG fuels, and also by reducing fuel consumption. Carbon neutral fuels and renewable energy derived carbon-free fuels are regarded as sustainable energy, but it is considered to be difficult for the supply to catch up with the demand, as the fuel consumption of today's large marine engines is large. LNG fuels are more effective at reducing GHG emissions than conventional liquid fuels, but with LNG fuels, it is difficult for large marine engines to achieve a significantly higher thermal efficiency (reduction of fuel consumption) than existing diesel engines.

One possible measure of reducing fuel consumption is to enhance thermal efficiency by increasing the geometric compression ratio (hereinafter referred to as the compression ratio), but the optimal compression ratio changes depending on operating environment, such as engine operating conditions and fuel composition, and is not a constant parameter. Therefore, working jointly with the IHI Power Systems Co., Ltd. (IPS), IHI developed the world's first Variable Compression Ratio (VCR) system for large marine engines that can freely adjust compression ratio according to operating environment while the engine is running. Effectiveness of the VCR system was demonstrated with one of the world's largest test engines (6X72DF), installed in IPS's Aioi Plant (Japan) as shown in **Fig. 1**. As a result, VCR system can significantly reduce fuel consumption and GHG emissions under actual operating conditions, thereby contributing to "Reduce" in the recycling society. Also, the ignition timing can be optimally controlled in accordance with the fuel composition by controlling the compression end temperature of the premixed gas through adjustment of the compression ratio using the VCR system. This paper focuses on the benefits that can be obtained with the VCR system. For reports on structure, development tests, and detailed performance, refer to references (2) to (4).

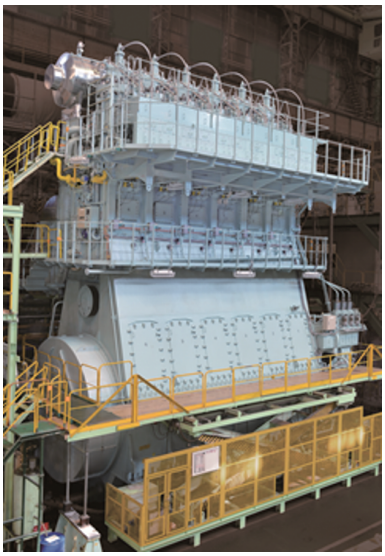


Fig. 1 2 stroke test engine in IPS (6X72DF)

2. VCR system developed by IHI and IPS

2.1 Concept of VCR system

This VCR system changes the compression ratio by changing the volume of the combustion chamber at the top dead center of the compression stroke (*Vc*), as shown in **Fig. 2**. **Figure 3** shows the VCR system that the authors developed for 2 stroke crosshead engines. As shown in the figure, the volume of the combustion chamber is changed by changing the projection length of the piston rod from the crosshead pin. This variable compression ratio method is used only for crosshead engines with a piston rod, and is different from VCR systems[5]–[9] developed for small engines.

Hydraulic oil is supplied to the lower hydraulic chamber located between the piston rod and crosshead pin so as to move the hydraulic piston up and down, thereby making the projection of the piston rod from the crosshead pin. The hydraulic oil needed to increase the projection of the piston rod is pumped by the plunger pump fixed to the crosshead pin. The hydraulic oil for the VCR system is branched from piston cooling oil, so that this VCR system does not require an additional hydraulic supply system, and therefore allows a simple, low-cost hydraulic system configuration. To decrease the projection of the piston rod, the hydraulic oil in the lower hydraulic chamber is discharged into the crank chamber from the relief valve secured to the crosshead pin. The VCR system in this study, which was manufactured for testing purposes, was designed so that the piston rod can project up to 100 mm from the crosshead, thereby making it possible to change the compression ratio from 12.0 to 18.0 in a stepless fashion.

2.2 Engine performance with VCR system

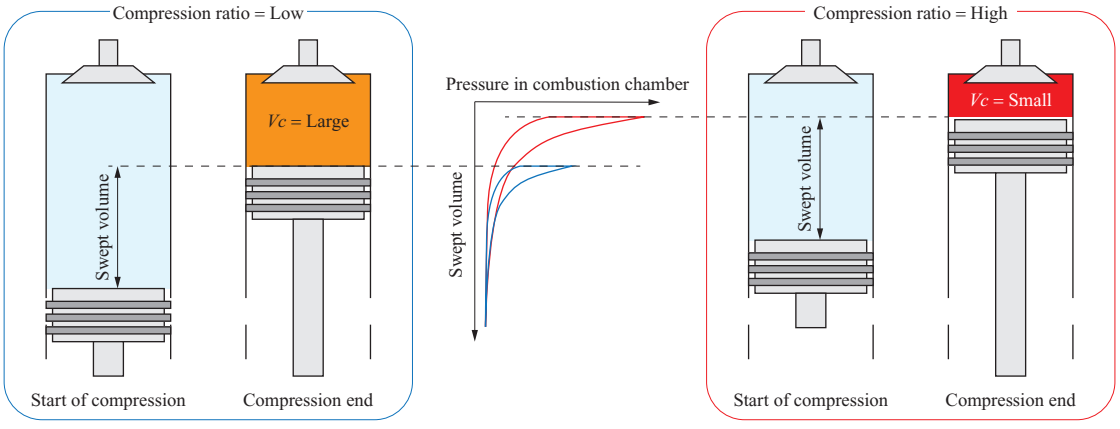
This VCR system was installed in one cylinder of an existing large marine engine to verify the operation of the system and evaluate its effect on operating performance and engine performance. As a result, VCR system operated as designed, and thermal efficiency of the engine improved as predicted[2]–[4]. In addition, the rate of increase in thermal efficiency was proportional to the theoretical thermal efficiency.

Figure 4 illustrates the combustion characteristics of the VCR system. It shows that the timing of self-ignition advances when the compression ratio is increased. This is because increasing compression ratio raises the compression end temperature of the premixed gas in the combustion chamber, which enhances fuel ignitability and thereby decreases the fuel ignition delay. This means that even if fuels with various combustion characteristics become commercially available due to SO_x regulations and expanded use of shale gas, engines with the VCR system can manage an appropriate compression end temperature with each various fuels.

3. Impact of VCR system on recycling society

3.1 Reductions in fuel consumption and CO_2 emissions

As previously stated, fuel consumption can be reduced significantly by using the VCR system to increase compression ratio. Newly built ships are designed to achieve optimal fuel consumption at the planned cruising speed (generally 75 to



(Note) *Vc* : Volume of combustion chamber

Fig. 2 Concept of Variable Compression Ratio

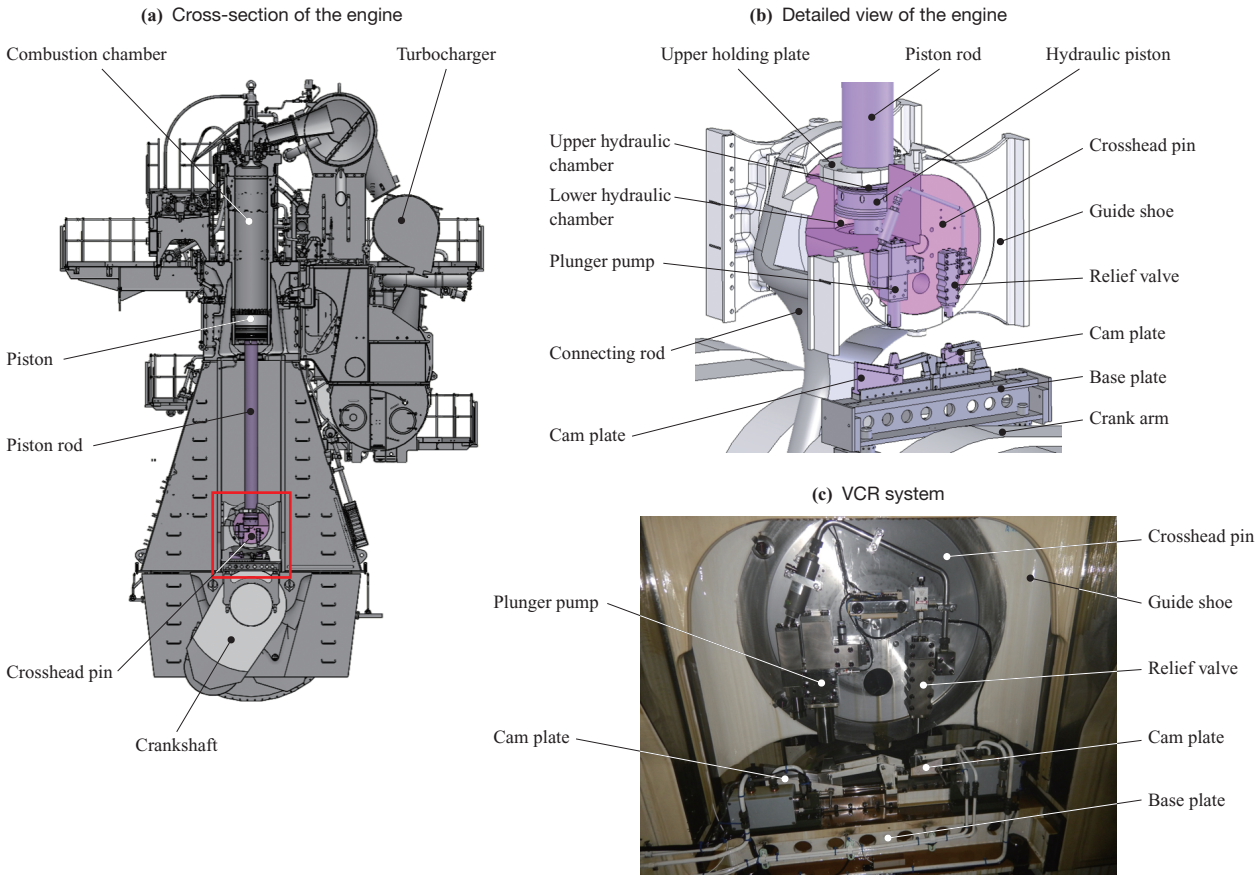
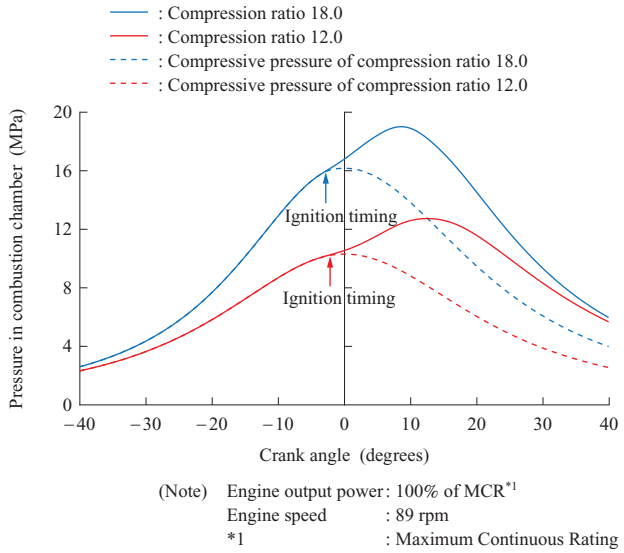


Fig. 3 Variable Compression Ratio system

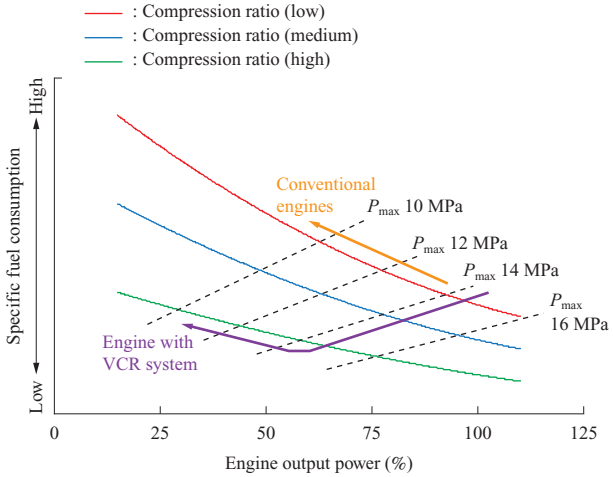


(Note) Engine output power : 100% of MCR*1
Engine speed : 89 rpm
*1 : Maximum Continuous Rating

Fig. 4 Cylinder pressure w/ and w/o VCR system

85% of engine output power). However, in practice, flexible adjustment of ship speed is necessary depending on cargo quantity, transport deadline, fuel cost, and other various factors; in particular, ships are required to operate at reduced speeds in order to reduce fuel costs. Ship speed and engine output power have a cubic relationship, and engine output power changes significantly when the ship speed increases or decreases slightly. Hitherto, it has been difficult to maintain optimal operation for such varying outputs with engines that have fixed compression ratios.

In general, when the compression ratio is fixed, the maximum combustion chamber pressure (P_{max}) decreases as output power decreases, and fuel consumption deteriorates accordingly. Here, within the design limit of P_{max}, the VCR system is used to increase the compression ratio as output power decreases, as shown in **Fig. 5**, thereby improving fuel



(Note) When P_{max} (maximum combustion chamber pressure) is limited to 14 MPa

Fig. 5 Concept of fuel consumption with VCR system

consumption — that has deteriorated with reducing output power to the former level or improve. However, depending on the range of variation of the compression ratio for the VCR system, the compression ratio may reach the upper limit of that range when the output is below a certain level, so that improvement of fuel consumption is limited to an extent.

For example, if a large containership is operated at reduced speed with an engine output of 45% Load[10] and annually operated for 7 000 hours by increasing the compression ratio with the VCR system, an annual fuel cost reduction of up to approximately 70 million yen (for a heavy oil price of 40 000 yen/k*l*), or an annual fuel consumption reduction of up to 1 500 tons (equivalent to approximately 4 500 tons of CO_2 emissions) can be expected. According to a survey conducted by the Ministry of Land, Infrastructure, Transport and Tourism, the number of large containerships (10 000 TEU or more) in service around the world is approximately 300[11]. If the VCR system was retrofitted to all of these ships in service and they were operated under the same conditions, there would be an annual reduction in fuel consumption of approximately 450 000 tons (21 billion yen), which is equivalent to approximately 1 350 000 tons of CO_2 emissions (the annual CO_2 emissions from approximately 140 000 people). This enables environmentally friendly transport and allows product cost to be reduced as a result of transportation cost reduction.

3.2 Combination with renewable energy; VCR system enables the flexible use of carbon-free fuels and carbon neutral fuels

Next-generation fuels, such as renewable energy derived carbon-free fuels and carbon neutral fuels (biomass) of renewable energy, have combustion characteristics that are quite different from those of conventional liquid fuels (e.g., heavy fuel oil), and some of these next-generation fuels have lower ignitability. Controlling the compression end temperature is an effective means of achieving optimal combustion of each of these next-generation fuels. With the VCR system, the compression end temperature can be controlled by freely changing the compression ratio, thereby achieving stable combustion even when next-generation fuels that have inferior combustion characteristics are supplied to the engines. Hence, the VCR system enables stable engine operation even with future fuels so that there is no need to demolish ships in service or build new ships in order to use new fuels. With this, a reduction of approximately 13 000 tons of CO_2 emissions per ship[12] can be achieved. According to a survey conducted by the Ministry of Land, Infrastructure, Transport and Tourism, newly built containerships are becoming increasingly large, and although there is a corresponding decrease in the number being built, the average stands at 100 to 150 ships per year[11]. If the number of newly built ships could be decreased through the VCR system, CO_2 emissions might be significantly reduced.

3.3 Reduction of transport time through more flexible operation planning

Due to strengthening of SO_x regulations regarding general sea areas in 2020, it is expected that liquid fuels having various combustion characteristics will become commercially available as a result of differences in low-sulfur fuel production methods. With regard to gas fuels also, it is possible that fuels such as shale gas, with combustion characteristics different from those of conventional LNG fuels, will become commercially available. Existing ships may need to call at ports for the sole purpose of bunkering (refueling with) fuels that are compatible with their engines. In contrast, ships that have engines with the VCR system are compatible with fuels of various combustion characteristics because compression ratio can be varied; this enhanced flexibility allows bunkering of a relatively large range of fuels. This makes it possible to bunker fuel at the same time as loading cargo, consequently allowing a reduction in bunkering time, and therefore transport time, which thereby contributes to a reduction of transport cost.

3.4 Advantages of retrofitting VCR system to existing ships

The structure of the VCR system developed by IHI and IPS allows it to be installed by replacing some of the parts in today's engine (crosshead pin, piston rod, connecting rod, and guide shoe). It can therefore easily be retrofitted to ships that are currently in service, thereby obtaining the previously stated benefits of the VCR system. Such retrofitting will make it possible to deal with future strengthening of EEDI (Energy Efficiency Design Index) regulations, SO_x regulations, and conversion to carbon-free fuels without building new ships. In addition, when considered in total, the CAPEX (CAPital EXpenditure) and OPEX (OPerating EXpenditure) of retrofitting the VCR system to a ship that is currently in service is expected to be lower than that of building a new ship.

4. Conclusion

The VCR system for large marine engines is a world's first technology and won the award for Marine Engineering of the Year (Doko Memorial Prize) in 2018, from which it is clear that this technology is receiving a large amount of world's attention. These research achievements of IHI and IPS have been highly evaluated, and with the aim of commercialization in the near future, IHI and IPS have agreed with licenser WinGD (Winterthur Gas & Diesel) to jointly develop the VCR system for commercial use. Diligent work is currently in progress aimed at accelerating development.

When this VCR system for commercial use is completed and, as previously reported[13], combined with the X-DF engine, which holds an overwhelming market share, it is expected that the result will constitute an unprecedented large marine 2 stroke crosshead engine that can contribute significantly to a recycling society.

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