CIMAC CONGRESS 25
ZURICH, MAY 19 – 23, 2025

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# Compression without compromise: dynamic optimisation of combustion in dual-fuel engines with VCR

Basic research & advanced engineering - new concepts

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## ABSTRACT

With around 900 engines sold to date, WinGD's X-DF low-pressure dual-fuel engines have been well received in the marine market since their introduction in 2016. The engines have been developed continuously to further improve performance, emissions, and reliability. One of the most significant advancements was achieved with the introduction of the unique variable compression ratio (VCR) technology.

VCR technology allows the engine to continuously maximize compression ratio and fuel efficiency during operation, for any operating condition and regardless of the fuel mode used. As a result, the VCR delivers the lowest possible fuel consumption and methane slip in gas mode, eliminates the 'typical' fuel consumption penalty of Otto-cycle engines in diesel mode and allows greater flexibility in operation (e.g., enabling increased usage of power take-off via a shaft generator). With these features, X-DF engines clearly outperform other low-pressure dual-fuel engines in the market and compete with corresponding high-pressure dual-fuel types, while still being the more cost-effective option.

The technology was developed in cooperation with WinGD's engine builder partner MESDU in Japan, where it has been thoroughly tested on a designated 72-bore dual-fuel test engine. Since its launch in June 2023, more than 100 engines with VCR technology have been contracted in newbuilding projects. A first factory acceptance test and subsequent delivery of the engine to the shipyard has taken place in Q3/2024. WinGD is also carried out an upgrade of a container feeder vessel in service, which had its RT-flex50DF main engine converted to feature VCR in Q3/2024.

This paper describes the introduction of VCR technology to the market and discusses test results from the first production engines. WinGD's experience of retrofitting VCR to the existing installation is presented, as well as early in-service performance of the system. Finally, an outlook is provided on the benefits of applying this technology to engines running on alternative fuel types, such as methanol or ammonia.

# 1 INTRODUCTION

LNG-fuelled two-stroke marine engines have entered the merchant marine segment in the last decade, delivering favourable emission characteristics and attractive operating cost compared to conventional propulsion solutions. WinGD has developed and introduced its very successful series of X-DF LNG dual-fuel engines, which are based on the low-pressure, Otto-cycle combustion principle when running in gas mode. These engines have quickly become a standard in LNG carrier (LNGC) applications and have also been applied on many other deep-sea merchant ship types. To date, around 900 engines have been sold, with engines in service accumulating approximately 10 million running hours.

The main benefits of low-pressure dual-fuel engines compared to competing high-pressure counterparts are:

- Simple low-pressure gas supply and admission systems resulting in lowest CAPEX
- Lowest levels of pollutant emissions ($NO_x$, Particulate Matter, $SO_x$), Tier III $NO_x$ compliance without exhaust aftertreatment systems
- Lowest pilot fuel injection quantities
- Simple operation and maintenance of engines and ancillary systems

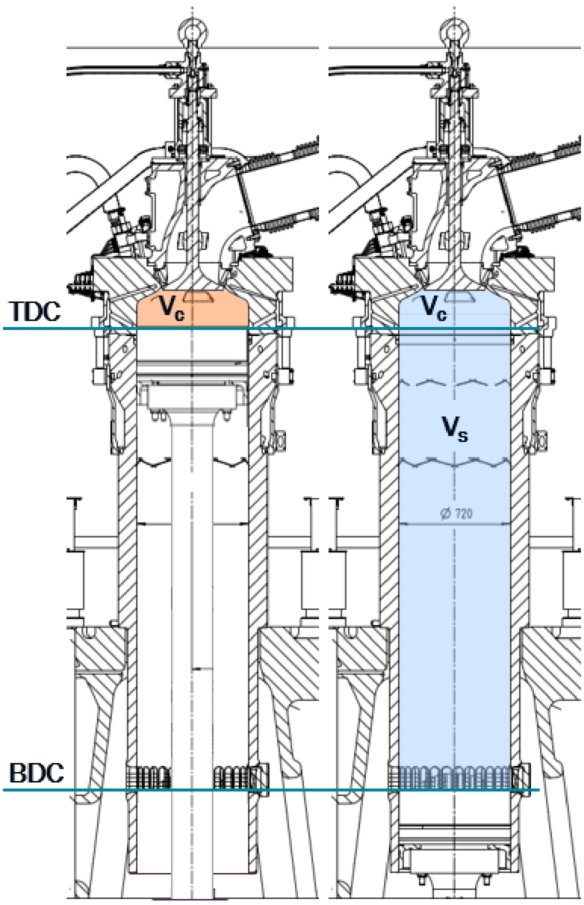
LNGCs usually operate on boil-off gas from their cargo. Low-pressure propulsion engines therefore have an inherent advantage as the gas needs to be compressed to about 13 bar only, in contrast to 300 bar or more for high-pressure engines. This leads to significantly reduced energy demand for boil-off gas compression and therefore to the lowest possible total energy demand and fuel consumption for this type of vessel.

On other LNG-fuelled applications, the difference in energy demand for pressurization of the gas is not as big, since the pressure of the LNG is usually increased in liquid state by pumps, rather than using compressors. Therefore, the efficiency of the main engine is a more important factor. This is particularly valid for diesel mode operation, in which such vessels are more likely than LNGCs to be operated.

Initial X-DF engines came with a fuel penalty in diesel mode due to the fact that the mechanical compression ratio had to be limited to a level where gas mode operation could be ensured under worst-case conditions. This disadvantage is eliminated with the application of Variable Compression Ratio (VCR) technology, which allows compression ratio to be maximised under any operating condition, thus achieving the highest possible efficiencies in both diesel and gas operating modes. Furthermore, the natural advantages of the low-pressure solution, such as lower CAPEX, lower maintenance cost and simple operation, remain valid on VCR engines.

The X-DF design concept and an earlier version of the VCR system have been presented at previous CIMAC Congresses [1], [2], [3].

The definition of the compression ratio is illustrated in Figure *1*.




$$CR = \frac{V_{BDC}}{V_{TDC}} = \frac{Vc + Vs}{Vc}$$

where:

*CR* .............. = Compression Ratio
$V_{BDC}$ ........... = cylinder volume at the Bottom Dead Centre [$m^3$]
$V_{TDC}$ ........... = cylinder volume at the Top Dead Centre [$m^3$]
$V_c$ ............... = compression volume [$m^3$]
*Vs* ............... = swept volume, defined as $V_{BDC}$ - $V_{TDC}$ [$m^3$]

Figure 1: Definition of compression ratio

The VCR system automatically maximises compression ratio for actual operating conditions, meaning that operation is not compromised by an optimisation for a design point in which the engine is usually not operated.

Accordingly, X-DF engines are not only the engines of choice for LNGCs but have re-gained competitiveness against high-pressure counterparts for other LNG-fuelled applications. This is particularly valid with the application of higher fuel consumption tolerances as introduced by another engine designer for its high-pressure dual-fuel engines in November 2024, which indicates higher effective consumption figures than previously stated in performance predictions. Such a difference in consumption tolerances must be included when comparing fuel consumption figures.

Figure *2* illustrates different competitiveness metrics such as annual fuel cost, typical CAPEX and annual greenhouse gas emissions (GHG) including methane slip. It can be seen how the X-DF engine versions have evolved over time to become the most competitive solution.

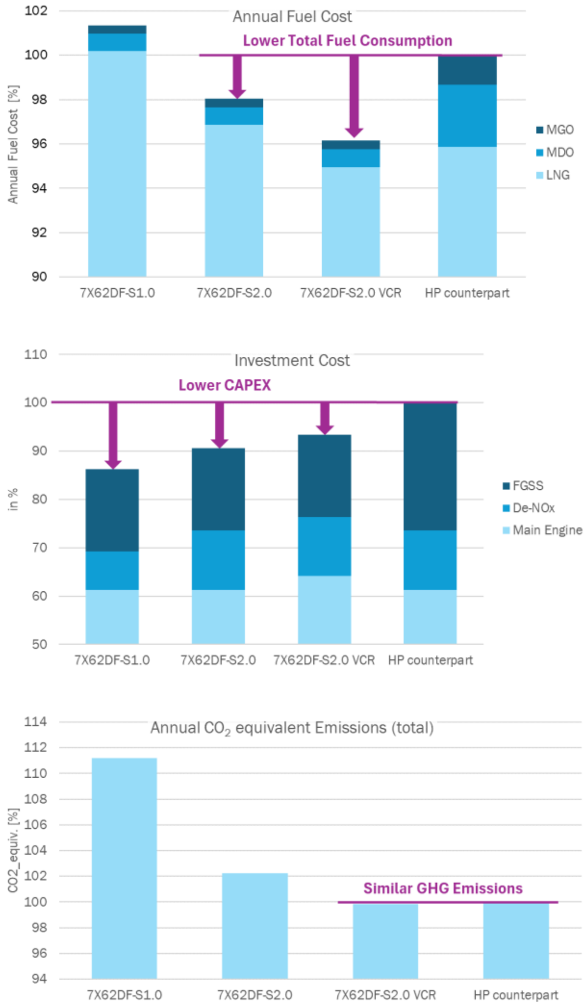



Figure 2: Fuel cost, investment cost and CO2 equivalent emissions in comparison to a high-pressure engine

VCR addresses general industry challenges such as fuel efficiency, GHG emission reduction and fuel flexibility. Furthermore, engines become more adaptable to varying operating conditions, including different load profiles, ambient conditions and use of power take-out (PTO) or other energy efficiency measures.

WinGD has noticed significant market interest in VCR technology in response to the above-mentioned industry challenges. More than 100 VCR engines have been ordered since the introduction of this new technology in mid-2023. Currently, the system is offered for 62- and 72-bore engines, with plans to introduce VCR technology across all X-DF bore sizes in the future.

# 2 ADVANTAGES OF THE VCR SYSTEM

## 2.1 Reduced fuel consumption

The VCR system allows to achieve consumption savings both, in diesel and gas mode operation. Figure *3* describes the consumption for diesel mode operation on a fixed pitch propeller (FPP) installation, as also available in WinGD's performance tool "General Technical Data" (GTD). Fuel consumption is significantly reduced throughout the load range and now comparable to the consumption of a corresponding diesel engine type. Therefore, the diesel consumption penalty of earlier X-DF engines is eliminated by the application of the VCR system.

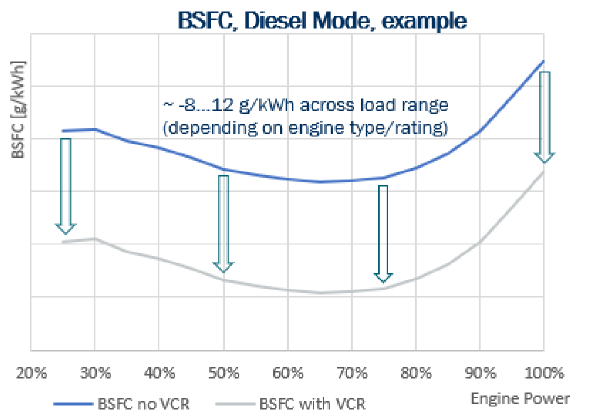



Figure 3: Diesel mode consumption savings with VCR

In gas mode operation, the consumption characteristics is different. Even with VCR, the compression ratio at full engine load is set to approximately the same level as on an engine without VCR, in order to avoid combustion issues such as pre-ignition or excessive combustion speed under worst case operation conditions. Whenever the engine is operated in part-load, the larger combustion margins can be utilized to increase compression ratio and increase efficiency. Accordingly, gas consumption savings increase at lower engine loads, as shown in Figure *4*.

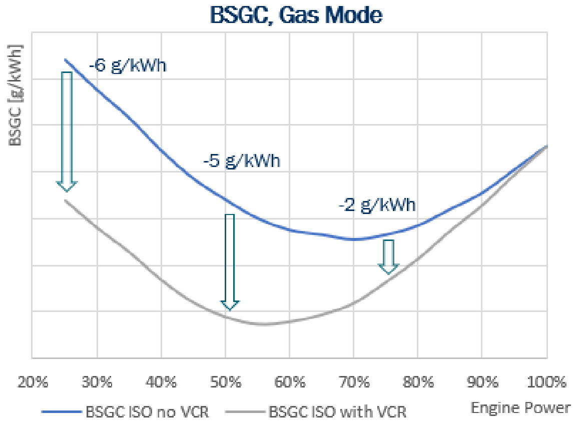



Figure 4: Gas mode consumption savings with VCR

For controllable pitch propeller (CPP) operation, larger efficiency gains can be realised as the engines typically run at lower torque, allowing CR and efficiency to be increased to a higher level. Chapter 6 presents these gains with actual test results on a pilot installation vessel, showing the efficiency gains by measured fuel consumption.

### 2.2 Reduced methane slip and GHG emissions

With a target to continuously improve the environmental performance of our products and with methane emissions being included in future emission taxation schemes, WinGD has invested significant efforts into reducing methane slip to lowest possible levels. While the first generation of X-DF engines has already featured industry-lowest methane slip levels for Otto-cycle combustion engines, numerous measures have been implemented in following generations of engines, such as optimizations of combustion chamber designs, engine tunings and most importantly, application if iCER exhaust gas recirculation systems. The latter technology has been introduced in 2020 and has achieved a reduction in methane slip by 40-50% compared to previous engines.

On the latest generation engines as described in this paper, a combination of iCER and VCR yields a further reduction of methane slip in part-load operation, because increasing CR in part-load operation allows higher exhaust recirculation rates while still maintaining combustion stability. Sizing of the iCER equipment remains the same, as it is designed for full load operation, but the utilization rate is increased at part load.

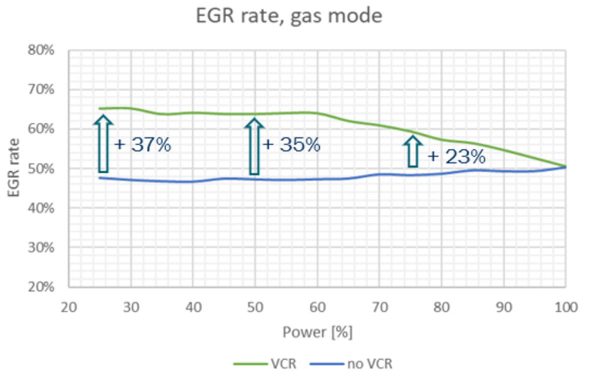



Figure 5: Increase of EGR rate with VCR

This increased exhaust gas recirculation leads to additional methane slip reduction using VCR, as shown in below Figure *6*. This results in very low slip levels of approximately 0.9 g/kWh, or less than 0.7% of total gas consumption across an IMO weighted average test cycle.

This means that X-DF engines with iCER and VCR deliver significantly lower methane slip than the default factor of 1.7% in FuelEU Maritime regulations for low-pressure low-speed dual-fuel engines. WinGD is working on proposing a more representative default factor. Until those are implemented, engines should be certified individually using test-bed measurements of methane slip from factory acceptance tests (FAT). WinGD recommends extending the regular $NO_x$ certification measurements on the parent engine of a series to include measuring and documenting methane slip.

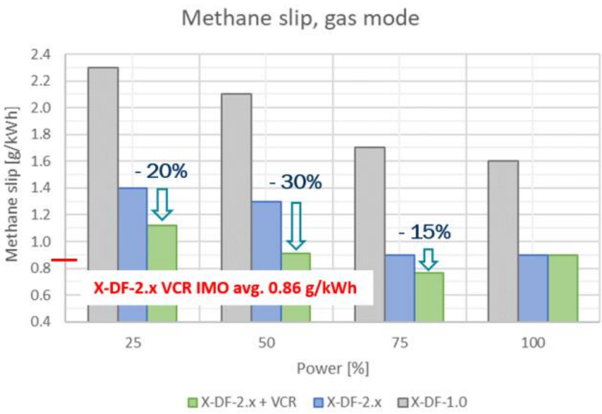



Figure 6: Evolution of methane slip over different generations of X-DF engines, 72-bore

### 2.3 Increased flexibility of operation

With VCR technology, engines can for the first time be adjusted automatically for different operating conditions (power/speed, ambient conditions, PTO operation, etc.,), therefore maximising efficiency continuously.

VCR technology also integrates effectively with efficiency measures on vessels, such as air lubrication systems or wind-assisted propulsion, that have an impact on the operating point (power/speed) at which the engine is running. The additional propulsive force generated by wind sails, or the reduced hull resistance delivered by air lubrication systems, result in the engine running at lower torque at a given power, which allows for an increase in CR and a further reduction in specific fuel consumption. As a result, the reduction in fuel consumption is achieved through the seamless interplay of two factors: first, the lower propulsion power demand enabled by the external measures, and second, the enhanced part-load efficiency of the main engine.

For installations with PTO, engines usually operate away from the design point, depending on whether the PTO is on or off. VCR automatically adjusts for this and utilizes any resulting margin. Additionally, the system increases available PTO power by reducing the CR if necessary. While this reduces the main engine efficiency to some extent, the efficiency of producing electric power is still higher compared to producing it via the auxiliary engines, and methane slip and overall GHG emissions of the overall propulsion system remain at the lowest possible levels.

### 2.4 Application of VCR to other combustion concepts

Diesel-cycle engines operate at a high CR by default and the benefits of applying a VCR system are therefore smaller compared to Otto-cycle combustion engines. However, even here consumption benefits can be realised in part-load operation, where engines typically operate most of the time. In contrast to the very large consumption savings on LNG dual-fuel engines, it is expected that savings of 1-2% can be achieved on Diesel-cycle engines, depending on engine rating, load profile and other factors.

For methanol- and ammonia-fuelled Diesel-cycle engines operated on expensive green fuels, VCR can offer reasonably short payback periods. Increasing the CR on these engines to even higher levels may require combustion chamber component design modifications to ensure that thermal loading of parts stays within permissible limits. While WinGD's first generation of X-DF-M methanol and X-DF-A ammonia engines are delivered with a fixed compression ratio, application of VCR on future generations of these engines is being considered in order to provide the most competitive engines to the market.

## 3 DESIGN

### 3.1 Mechanical Design

In comparison to the standard X-DF design, the VCR mechanical design includes a hydraulic piston, mounted on the lower end of the piston rod, which can vertically move into the crosshead pin designed with a bore.

The amount of hydraulic oil in the lower chamber defines the piston rod position, which determines the compression ratio. The upper chamber holds the piston down under any situation (e.g. engine start or malfunction of exhaust valve).

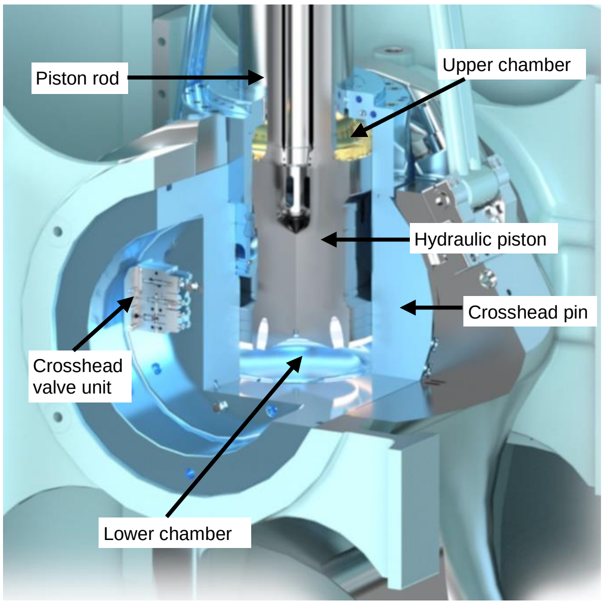



Figure 7: VCR main mechanical components

The valve unit mounted on the crosshead pin allows hydraulic oil to be distributed in the VCR system and consists of: the delivery valve, which admits oil in the lower chamber to lift the piston up; the outlet valve, which releases oil from the lower chamber to lower the piston; and the lift-off valve with filling orifice, which retains oil volume in the upper chamber to avoid lift-off of the piston, in case of low oil pressure in the lower chamber.

The valve unit mounted on the column fuel side allows for each cylinder to control the hydraulic oil in the VCR system. On each unit a knee lever connects both valve units to convey the hydraulic oil.

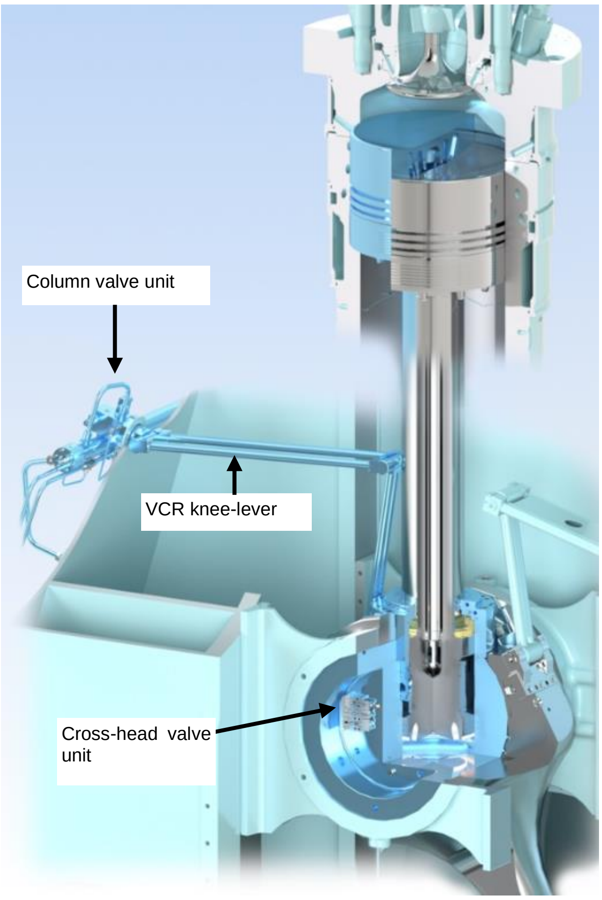



Figure 8: Valve units and knee-lever

The feed pump (electrically driven) is mounted on the free end of the engine and increases the engine lube oil pressure from approx. 5 bar to the feed pressure of approx. 50 bar. The pump is reasonably small with a nominal electric power of approx. 15 kW only and since a variable speed electric motor is employed, the power consumption is reduced to less than 5 kW in normal operation when the compression ratio is kept stable.

The feed manifold distributes the hydraulic oil to all cylinders via the valve units mounted on the column fuel side. The pressure control valve limits the pressure in the feed manifold in case the pump speed control acts too slow during transient operation.

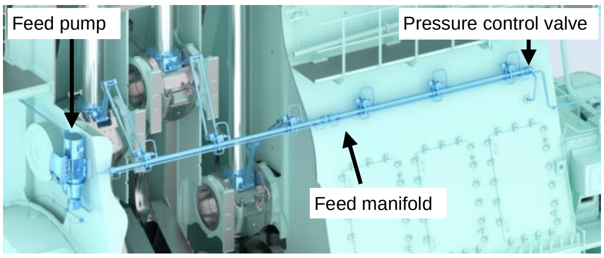



Figure 9: VCR Feed system

### 3.2 Electronic control

The VCR system is controlled by WinGD's standard WiCE engine control system. The position/compression ratio of each piston is close-loop controlled, with the following sensors delivering inputs for the system:

- The piston position sensor measures piston timing and enables control of piston rod position.
- The air temperature sensor at the piston underside measures the scavenge air temperature close to the scavenging ports of each cylinder. This signal is used as one of the parameters for determining the compression ratio setpoint, with colder temperatures allowing higher compression ratio and vice-versa.
- The $O_2$ sensor at the piston underside measures the $O_2$ concentration and allows precise control of the EGR rate when operating in gas mode at high compression ratio.

The position of the piston is controlled by two electric control valves shown in Figure 10:

- The solenoid proportional valve controls the oil flow amount delivered to the lower chamber
- The solenoid relief valve controls the oil flow out of the lower chamber

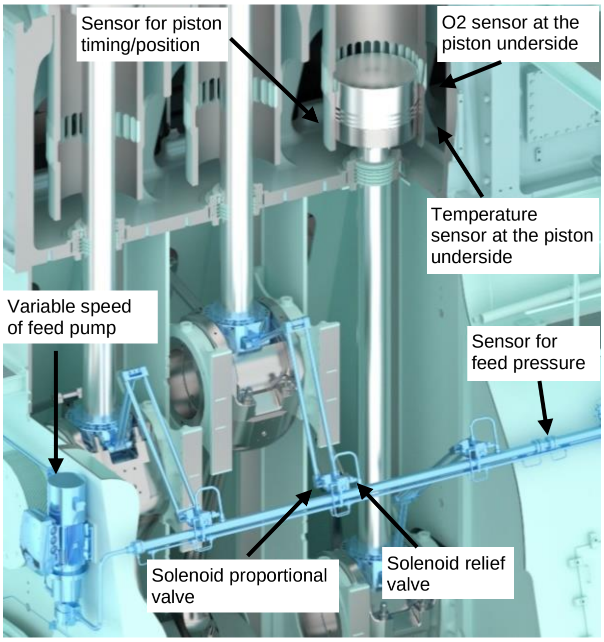



Figure 10: Installation of VCR related engine control components

The control diagram in Figure *11* describes the VCR hydraulic system including piston cooling and crosshead lubrication.

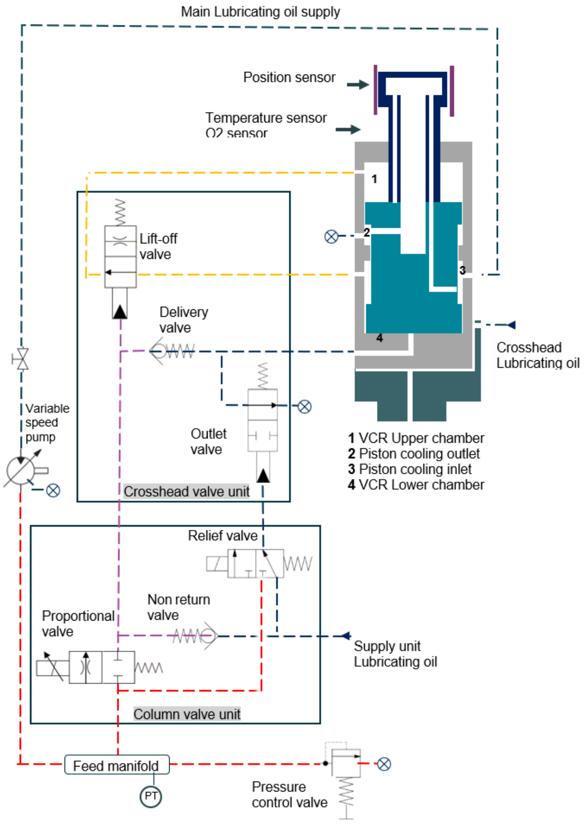



Figure 11: VCR Control diagram

### 3.3 Fail-safe design

The fail-safe design concept ensures that in case of VCR failure, propulsion power remains fully available up to 100% load.

In case the VCR is not working, the piston will be pushed to the lowest mechanical end-stop and kept in position by gas forces from the combustion chamber/piston which are greater than mass forces during normal operation of the engine. To avoid lifting of the hydraulic piston in other cases such as during engine start or in case of an exhaust valve failure (which would not build up cylinder pressure), the upper hydraulic chamber will hold the piston in its lowest position as shown in Figure *12*.

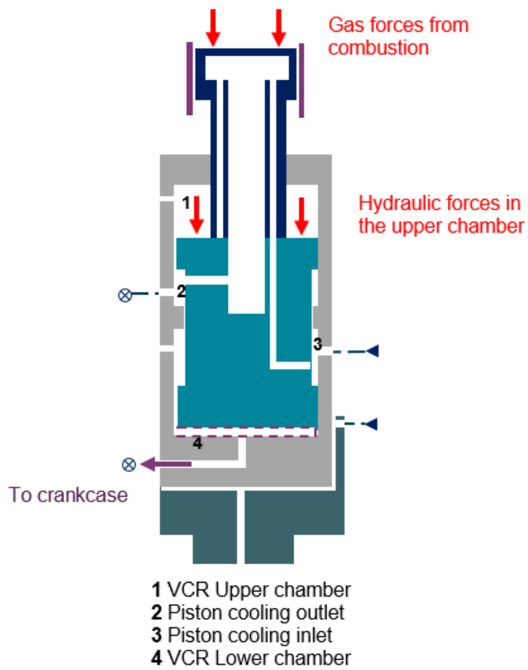



Figure 12: VCR Fail-safe design

Standard system oil is used for the VCR mechanism without any additional filtration or quality requirements, same as for lubrication, cooling, and other hydraulic systems on the engine. Accordingly, any leakage or release of oil is simply drained into the crankcase.

## 4 OPERATION

VCR is meant to be in operation continuously in both gas and diesel mode. Control of the VCR is fully integrated into the engine control system and there is no need for the operator to adjust or interfere in any way. A specific page is made availble in the WiCE user interface to monitor the parameters relevant for operation of the VCR system and manually activate certain components for trouble shooting support, in case that would be needed.

### 4.1 Operating modes

An overview of available operating modes is shown in Figure *13*.

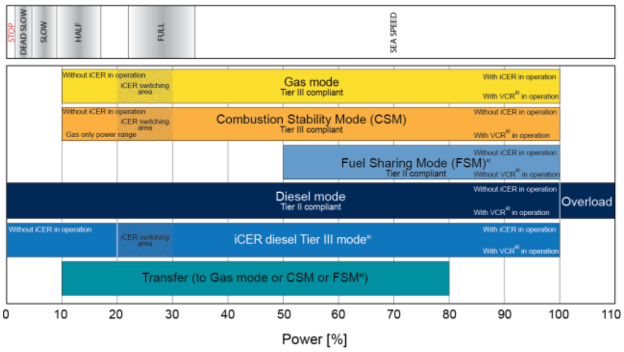



Figure 13: Operating modes of a VCR engine

While VCR is continuously active in the main operating modes (gas mode, diesel Tier II and Tier III mode), the engine can also be operated in case of a VCR failure, to ensure propulsion at any time. As illustrated in Figure *14*, in case of a failure of the VCR system, the engine will automatically trip to the *VCR fallback diesel mode*.

From *VCR fallback diesel mode*, the engine can be transferred to *Combustion Stability Mode* (CSM), in which it will burn gas with an increased amount of liquid fuel to retain combustion stability. This means that even in case of a failure of the VCR system, the engine can continue to burn a large share of gas, which is an important factor for the boil-off gas (BOG) management on LNGCs.

The engine remains available to operate on both diesel and gas fuel in case of a VCR failure because the system is not needed for maintaining propulsion power, but it is rather a tool to maximise engine efficiency.

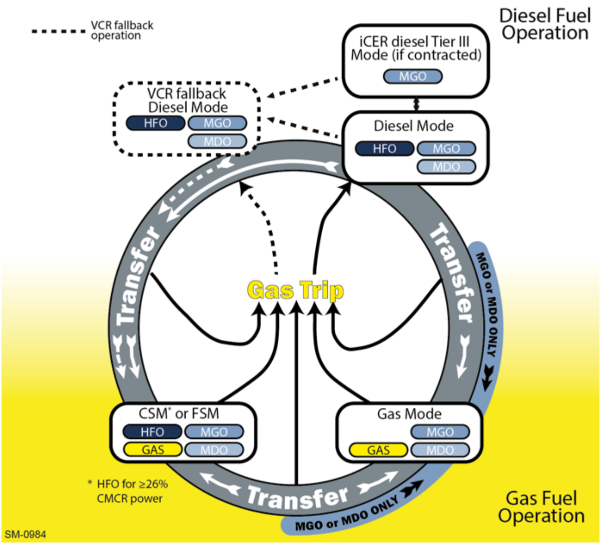



Figure 14: Overview of operating modes and transfers

### 4.2 Maintenance concept

The VCR system has been designed for lowest possible additional maintenance and for component time between overhaul (TBO) times to fit regular five-year drydock intervals. The hydraulic mechanism fitted in the crosshead pin does not include any wear parts such as rubber sealings and is expected to remain in the engine without the need for maintenance for the engine lifetime.

However, until long-term service experience is available, it is recommended to replace selected components at five-year intervals to ensure that the VCR function remains available at any time. Components to be replaced include the gearwheel pump, the bearings of the electric motor and the frequency inverter of the feed pump unit. Other components such as the knee lever for the oil feed, the solenoid valves and related sensors are expected to remain functional for a much longer period and a pro-active replacement is not foreseen.

Having related spare parts on board will ensure that the system can be put back in operation quickly, after an unexpected failure. The list of recommended spare parts as well as TBO times will be kept up to date based on actual operating experience of engines in service.

Piston removal is one example of how maintenance friendliness is incorporated in the design of the system. The engine's pistons may have to be removed at intervals, for instance to replace piston rings. For this operation, the hydraulic pistons do not need to be removed; instead, the piston rod can be disconnected from the hydraulic piston by removing the row of bolts with which they are fitted together. This ensures that the hydraulic system does not need to be opened, which minimises the risk of getting dirt particles into the hydraulic side, which could cause a problem when the engine is being put back in operation.

Due to the limited scope of parts to be replaced for regular maintenance, the additional efforts and cost caused by the VCR system are insignificant in comparison to the overall gains.

## 5 FIRST PRODUCTION ENGINE

MESDU (Mitsui E&S DU) is a long-standing builder of WinGD engines and has been closely involved in the development works of the X-DF LNG dual-fuel engine series. It has also been an integral partner in the development of the VCR system. As part of this cooperation, MESDU has conducted numerous tests on an R&D test engine installed in their Aioi works and has acquired significant knowledge in developing and validating engine designs and systems. It has therefore been valuable to have the first VCR production engines built and tested by MESDU.

As of end of January 2025, the first two production engines have been shop-tested and delivered to the shipyard and the Type Approval Testing of the VCR system has been successfully concluded with attendance of all major classification societies. Particulars of the first VCR production engine are shown in Table *1*. The engine will be installed on a NYK-owned bulk carrier to be built at the Oshima Shipyard [4].

Table 1: Main particulars of first production engine with VCR

| | |
|---|---|
| **Engine Type** | DU-WinGD 6X62DF-2.1 VCR |
| **Bore** | 620 mm |
| **Stroke** | 2,658 mm |
| **Rated Power** | 9,400 kW |
| **Rated Speed** | 81 $min^{-1}$ |

### 5.1 Manufacturing experience, challenges

Most of the components of the VCR system are manufactured according to common principles that are well known to engine builders and no special requirements apply.

One exception is the surface treatment of the hydraulic parts in the crosshead (the hydraulic piston and the bore in the crosshead pin), where the sliding surfaces are specified with a specific local surface hardness requirement. This is to avoid seizing or wear of components which would lead to a system failure or reduced lifetime of the components, which are expected to remain in the engine for its lifetime.

To fulfil this requirement, laser hardening is applied to the surface of the sliding parts, which are the inside of the crosshead bore and of the outer surface of the VCR piston. Upon manufacturing of the first components, Magnetic Particle Testing (MT) inspection revealed several small surface cracks in the laser hardened parts, as shown in Figure *15*.

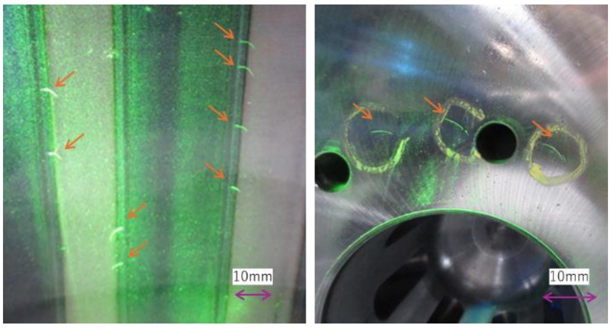



Figure 15: Cracks on laser hardened surface. Left: crosshead pin, right: VCR piston

Cracks were concentrated in the laser overlapped area at the boundary of each laser irradiation. Investigation showed that the overlap area was quenched by the first laser irradiation and then heated again by the second laser irradiation, causing annealing, as shown in Figure *16*a.

It was inferred that cracking occurred due to stress concentration in the area where inclusions were present because the hardened area was annealed once more, so laser hardening was performed by eliminating the overlapped area to minimize the annealed area.

Figure *16*b shows a cross-sectional macro photograph when the overlap is eliminated. It can be seen that the area of annealing has been reduced by eliminating the overlap.

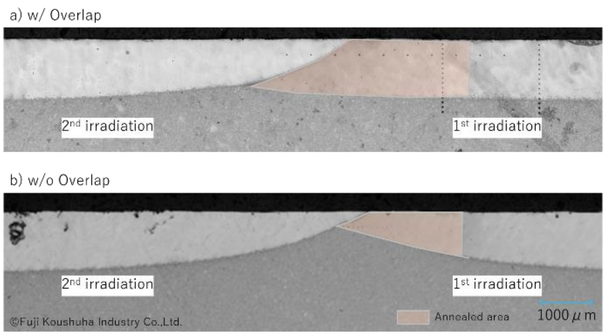



Figure 16: Cross macro photo. a) with overlap, b) without overlap

Figure *17* shows the hardness distribution at the boundary of the laser irradiation at a depth of 0.3 mm from the surface. Although the low hardness (soft) zone is a little wider without overlap, it is sufficiently small in relation to the curvature of the sliding surface that it is not a problem.

As a result of laser hardening according to this specification, no cracks were observed. The subsequent open inspection showed no expansion of the soft zone and no scratch damage. By optimizing the overlap, cracking was prevented while keeping the hardness.

Other components were manufactured by MESDU without any mentionable issues.

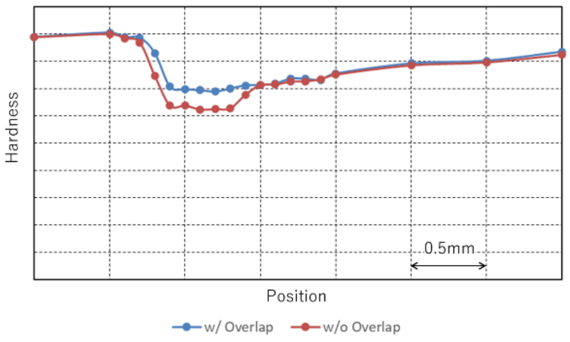



Figure 17: Hardness distribution around the boundary of the laser irradiation

### 5.2 Assembly and commissioning

Assembly of the VCR system on the engine was carried out by MESDU personnel without any remarkable issues. An experienced team of WinGD engineers supported MESDU for commissioning and the occasion of putting the first engine into operation was used to create a guideline to describe the best practice working procedures for commissioning of future VCR engines.

### 5.3 Operation of the VCR system

During the testing and optimisation campaign of the first engine, the VCR system was shown to work very well without causing any unexpected issues.

The turbocharger matching procedure is carried out in the same way as for a non-VCR engine. This is because the matching is done in gas mode at full engine load, in which the compression ratio and resulting performance of a VCR and non-VCR engine is the same. Accordingly, the TC specifications between the two engine versions remain the same.

During the entire testing operations, the compression ratio was kept at the intended position, defined by the compression ratio settings and the optimisation algorithms that are part of the engine control system.

### 5.4 Overhaul inspection results, components

After testing of the first production engine, a thorough inspection of all VCR related component was carried out. All components were found in good condition and no indications of any design or manufacturing issues were found. A few examples of components are shown in the following pictures.

Figure *18* shows the piston ring pack in good condition with no sign of thermal or mechanical overload.

Figure 18: Condition of piston ring pack

Figure *19* shows the crosshead bearing shell in normal condition with regular and even load carrying pattern.

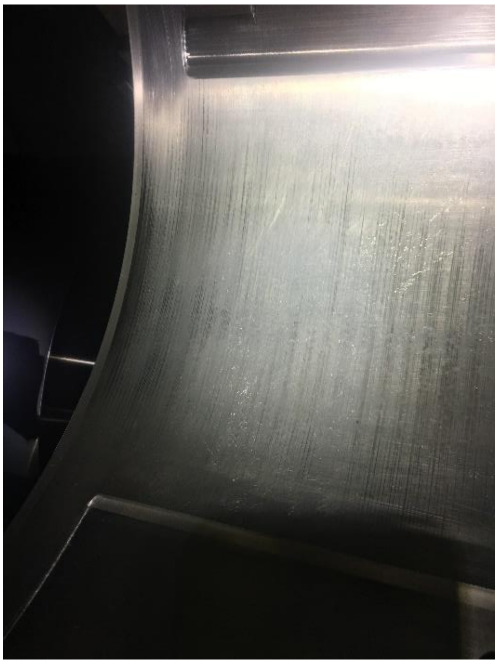


Figure 19: Condition of crosshead bearing shell

Figure 20: Hydraulic piston assembly

Figure *20* shows the hydraulic piston with good surface quality and no exceptional running marks, scratches or unexpected signs of wear.

Figure 21: Condition of hydraulic bore in crosshead pin

Figure *21* shows the cylinder bore in the crosshead pin with regular running marks and good quality of the laser hardened surface.

The component inspection concluded with good results and a confirmation that the system is fit for onboard use.

### 5.5 Feedback of customer

The customers have expressed their appreciation of the reliable operation of the system and that the compression ratio was well controlled between the different cylinders. Additionally, the customers have recognised the simplicity of the design of the VCR system.

### 5.6 Test results

As for every new engine type, an extensive optimisation test was carried out by WinGD and the respective engine builder with the target to verify proper operation of the engine and to minimise fuel consumption and emissions. Additionally, specific measurements are taken to verify that WinGD's design and calculation models reflect the situation observed on the first engine.

Since optimisation of engine performance is one of the main targets of the VCR system, the most important achievements are presented here. These results do not represent the final FAT measurements but are based on recordings of WinGD internal tests.

#### 5.6.1 Diesel mode operation:

When operating in diesel mode, the compression ratio is increased to a similar level as on a comparable diesel engine, which in this case is achieved by an increase of compression ratio of 8.8 points. In this operating mode, the compression ratio is kept constant across the entire load range of the engine, as shown in Figure 22.

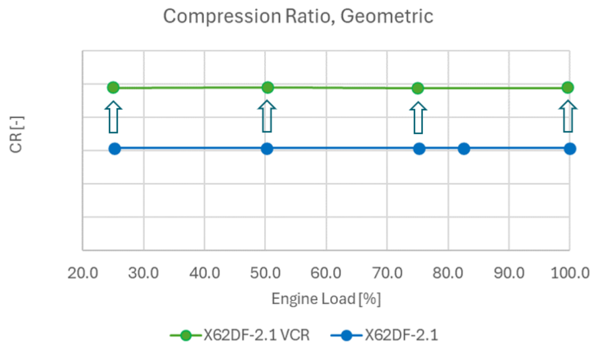



Figure 22: Compression ratio in diesel mode

This increase of compression ratio leads to a higher efficiency of the engine in diesel mode. Savings of 4.6% to 6.9% compared to a non-VCR engine were measured as shown in Figure 23. Both engine tunings are IMO Tier II $NO_x$ compliant.

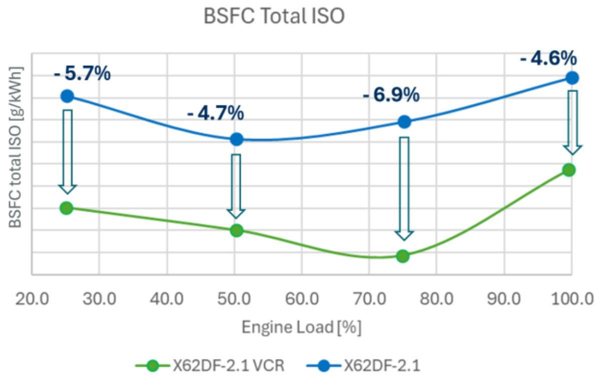



Figure 23: Fuel consumption in diesel mode

These results confirm that the VCR system eliminates any fuel consumption penalty in diesel mode, as opposed to earlier X-DF engines. Especially for LNG-fuelled vessels that may operate on liquid fuels for some time of their operation, this is a significant advantage.

### 5.6.2 Gas mode operation:

Unlike in diesel mode, the compression ratio in gas mode is not constant but varies according to engine load and other parameters. While the compression ratio at full engine load is similar to the non-VCR engine, operating at part load results in increased combustion margins, which are utilised by the VCR system to increase the compression ratio and maximise engine efficiency. Figure *24* shows the increase in compression ratio over engine load at the given operating conditions.

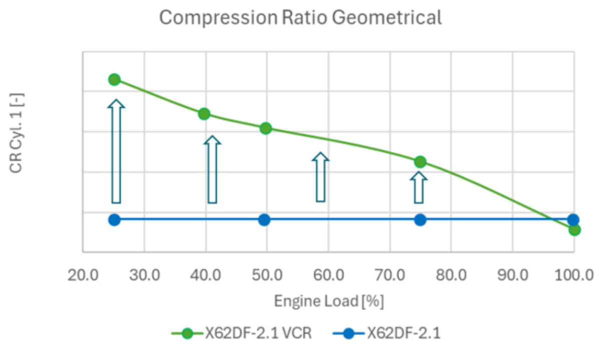



Figure 24: Compression ratio in gas mode

The increase of compression ratio in part-load operation further increases the amount of exhaust gas that can be recirculated, as shown in Figure *25*. Test results have shown that the best engine efficiency can be reached at maximum EGR rate and compression ratio. The limiting factors are the remaining air-fuel ratio of the combustion for the EGR rate and the maximum combustion pressure/speed for the maximum achievable compression ratio. With this strategy, EGR rates of more than 60% are possible. Since such high EGR rates are only used in part-load operation, the capacity layout of the EGR system is not affected and the system is used more effectively when the engine operates at part load, where typical propulsion engines are operated most of the time.

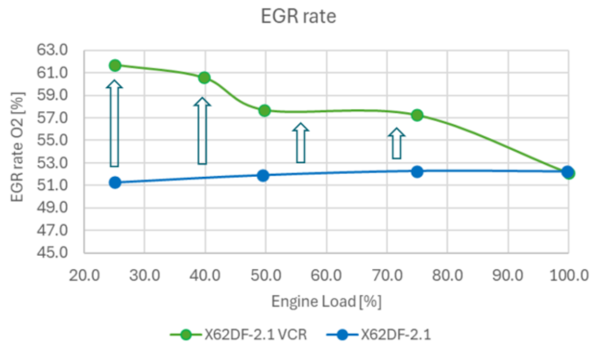



Figure 25: EGR rate in gas mode

Figure *26* shows the achieved reduction on energy consumption (gas and pilot fuel combined) compared to an engine without VCR. While the 50% load point was not yet fully optimised in terms of engine tuning, the other load points clearly show that the predicted fuel consumption savings can be achieved with VCR in operation.

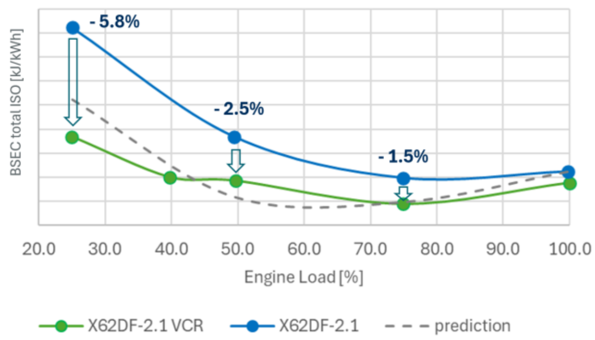



Figure 26: Energy consumption in gas mode

Another major improvement was seen in the measured methane slip figures, which were up to 33% lower compared to the previous engine tested without VCR. This reduction is not only achieved by the effect of the VCR system, but through an additional improvement, with smaller gas admission valves and nozzles also contributing to lower levels. It was earlier identified that the ‘dead volume’ in the gas nozzles significantly contributes to methane slip. This test confirmed that a reduction of such volumes directly leads to reduced slip levels.

As shown in Figure *27*, a methane slip level of an IMO weighted average 0.83% of the total gas consumption has been measured on this 62-bore engine. This is significantly lower than what has been achieved on comparable engine types previously. As mentioned earlier, this level of methane slip also shows that the FuelEU Maritime default emission factor of 1.7% is not representative for the latest generation of X-DF engines. Accordingly, WinGD suggests exercising an engine-specific certification based on actual FAT measurements of methane slip, which is explicitly allowed by regulations. This will allow for engines to be certified at much lower methane slip figures than given by the default factor, reducing future emission penalties accordingly.

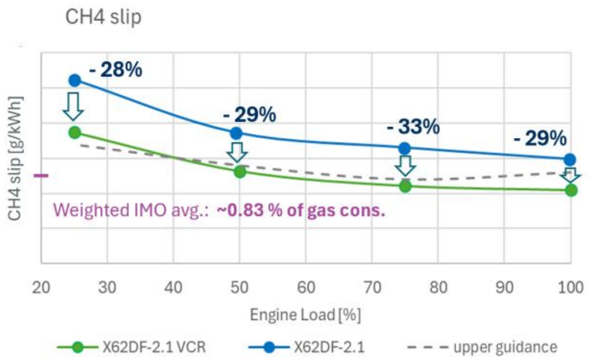



Figure 27: Methane slip measurements

Measured $NO_x$ emission levels are shown in Figure *28*, where it can be seen that VCR operation has no significant impact on $NO_x$ emissions, with $NO_x$ levels remaining far below the relevant IMO Tier III limits.

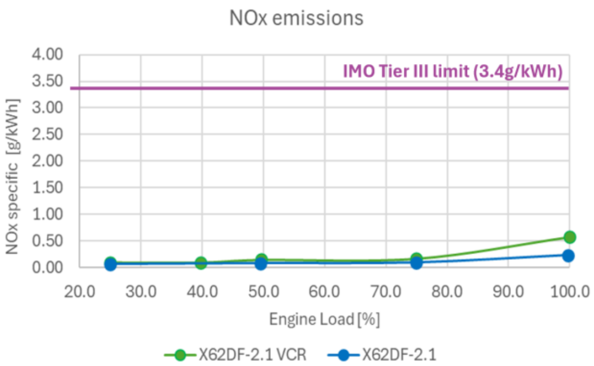



Figure 28: NOx measurements in gas mode

With these achievements the VCR system has proven to deliver the predicted advantages in terms of performance and emissions, as well as reliability of operation.

# 6 VCR PILOT INSTALLATION ON CONTAINERSHIPS AURORA

On its way to reach Net Zero Carbon by 2050, CMA CGM is committed to deploying sustainable solutions across its fleet, on both new built and existing ships.

While WinGD's aim was to validate the VCR technology on a seagoing vessel and to gain operation experience, CMA CGM is striving to apply technologies to reduce the carbon footprint of their fleet.

Both companies, CMA CGM and WinGD agreed to cooperate on a pilot installation to prove the OPEX benefits, the emission compliance and the reliability and operability of the technology.

## 6.1 Pilot installation

The vessel selected for the pilot installation is *CS Aurora*, a 1,400 TEU feeder container vessel sailing between the Baltic Sea and North Sea. It features a WinGD 7RT-flex50DF engine.

The engine is acting directly on a CPP system. In addition, a PTO system is accommodated in the shaft line. With this, *CS Aurora* is an optimal installation on which the operation flexibility of the VCR can be fully exploited.

The vessel was subject to a major overhaul during its five-year dry dock, including overhaul of all major machinery systems.


Figure 29: Containerships Aurora

The pilot installation project was structured in four major phases:

- A period of six months of data collection prior to the conversion.
- Engine conversion to VCR.
- Commissioning, engine tuning and optimisation.
- Evaluation phase, 3,000 running hours (around six months) of commercial operation and data collection.
- Final assessment and comparison of the data collected prior to and after the conversion.

## 6.2 Engine retrofit

The retrofit of the engine with VCR comprised various modifications and the following components are replaced for each unit: cylinder liner, piston rod, crosshead pin and guide shoes as well as the connecting rod.

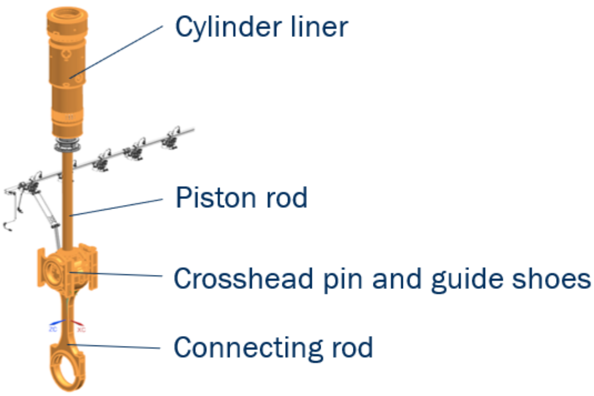



Figure 30: Components to be replaced for each cylinder unit

Further, new components are added: the VCR feed system including pump, piping and knee levers as well as control cabinets for the VCR Input/Output signals.

On this particular engine, the column had to be modified with new cutouts to add space for the additional knee levers and the assembly of the feed system.

Figure 31: Installation of crosshead pin

The installation was completed within the time during which the vessel was overhauled, repainted and fitted with a new bulbous bow. No extension of the scheduled dry-docking period was necessary to fit the VCR components.

## 6.3 Commissioning, tuning and optimisation

After the conversion the engine was re-commissioned, and all safety-relevant functions were tested at berth. *CS Aurora* left the shipyard and went for gas bunkering to Zeebrugge, after which commercial operation started on time with a first trip to Helsinki.

A team of WinGD engineers was onboard and performed an extensive tuning and optimisation campaign during regular operation. The vessel operated seamlessly with VCR active right from the start and no major operational issues were observed during the first weeks of operation.


Figure 32: CS Aurora operating route (source: CMA CGM)

As the vessel has a very particular itinerary and load profile, with a portion of low-load operation through the Kiel Canal and another big portion of 75% load operation in the North Sea, the tuning optimisation was focused on those operating points.

## 6.4 Consumption measurements

The resulting consumption fully complies with the predictions. While the fuel savings in Chapter 2 are described for FPP operation, *CS Aurora* operates on a CPP, and for this reason achieves larger consumption savings. This is because part-load operation at higher speed results in lower engine torque, which in turn allows CR to be increased to higher levels.

Additionally, this engine is not equipped with an iCER system, which changes the behaviour of the engine. As shown in Figure *33*, large gas consumption savings of 5% and 8.2% could be measured at 75% and 50% load respectively at a constant engine speed of 124rpm.

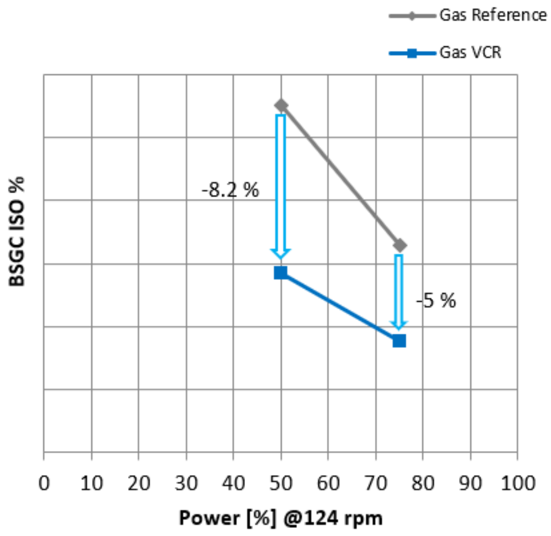



Figure 33: Gas mode CPP savings

With operation at 110 rpm, the VCR shows a significant impact in low-load gas mode operation, with extreme savings of 24% at the 15% load point.

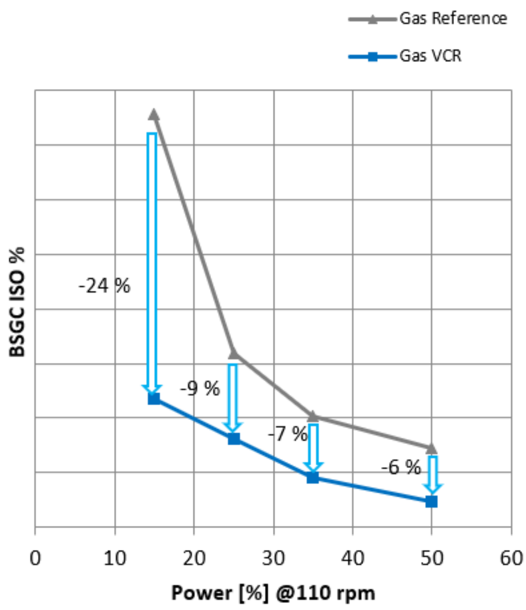



Figure 34: Gas mode CPP savings at low load operation

Further, the diesel fuel savings are in line with predictions, with more than 7% lower consumption compared to operation without the VCR system in use.

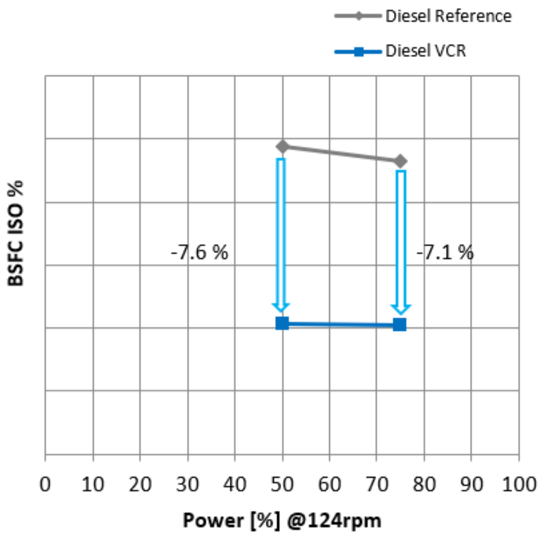



Figure 35: Diesel mode CPP savings

These fuel and gas consumption savings could be achieved while being fully compliant with $NO_x$ emission limits.

The field test period was still ongoing at the date of submission of this paper and final conclusions will be made after the vessel has run 3,000 running hours with VCR active.

### 6.5 Operational experience

After the tuning and optimisation campaign, the WinGD experts left the vessel and the engine with the VCR system was handed over to the crew. During operation, VCR does not require any interactions by the crew as the actuation is fully implemented in the engine control system.

From the start, VCR displayed flawless operation, with full availability of all functions throughout the engine running time of more than 1,100 running hours by the time of submission of this paper.

### 6.6 Learnings

Although the field test period is not concluded yet, the pilot installation on *CS Aurora* has shown so far that a retrofit of the system can be performed during a regular dry dock, and that after commissioning at berth, the engine can be tuned during commercial operation at sea by WinGD's experts.

Based on those learnings WinGD will be in the position to offer retrofit packages for engines in the operating fleet and to provide proper tuning while the vessel is seagoing and in normal operation. The VCR system can be fitted within the existing engine boundaries and poses no additional engine room space or interface requirement. Considering the significant fuel and gas savings over the load range, WinGD is confident that the VCR technology offers short return on investment periods not only in newbuilding, but also for retrofit installations.

## 7 CONCLUSIONS

The VCR system represents the latest advancement in WinGD's successful X-DF low-pressure dual-fuel technology, making it the most competitive main propulsion engine for LNGCs and other LNG-fuelled ship types.

Its simple design allows reliable operation at the highest possible efficiencies regardless of the chosen fuel mode (gas or diesel) and operating conditions while still maintaining the CAPEX and OPEX benefits inherent in earlier X-DF engine designs. Its characteristics of maximising efficiency of the engine in combination with other energy saving devices such as air lubrication of wind assisted propulsion make it a perfect fit for modern ship designs, where flexibility and efficiency are key criteria.

First production engines have been built, tested and delivered to the shipyard, with positive manufacturing experience from the engine builder MESDU in Japan. First VCR versions of the popular X72DF type will be delivered from engine builders in Korea within 2025 and the expansion of VCR applications to the full X-DF engine portfolio is ongoing.

A 1,400 TEU container feeder vessel with an RT-flex50DF main engine has been upgraded with a VCR system and has been in commercial operation for some time, where very positive seagoing experience was collected. Besides confirming reliable operation of the system under actual seagoing conditions, very significant fuel consumption savings could be demonstrated, of approximately 5-24% in gas mode and more than 7% in diesel mode, compared to operation without the VCR system.

The positive experience with VCR has created a large market interest for newbuilding and retrofit projects, with more than 100 newbuilding contracts secured. Designs and specifications are fully available for newbuilding projects and WinGD is preparing an offering for retrofits of existing installations, based on experience gained as part of the pilot project.

VCR also provides consumption benefits on Diesel-cycle engines, including methanol and ammonia fuelled versions. While the savings are smaller than on LNG dual-fuel engine types, the expected 1-2% reduction in consumption is expected to pay off within reasonable durations when operating on expensive green fuels. Accordingly, WinGD is evaluating the implementation of VCR on future versions of its X-DF-M methanol and X-DF-A ammonia engine types.

## 8 DEFINITIONS, ACRONYMS, ABBREVIATIONS

| | |
|---|---|
| BOG | Boil-off gas |
| BSFC | Brake specific fuel consumption (Diesel) |
| BSGC | Brake specific gas consumption |
| CAPEX | Capital expenditures (investment cost) |
| CPP | Controllable pitch propeller |
| CR | Compression ratio |
| EGR | Exhaust gas recirculation |
| FAT | Factory acceptance test |
| FPP | Fixed-pitch propeller |

| | |
|---|---|
| GHG | Greenhouse gas emissions |
| GTD | General Technical Data (WinGD performance tool) |
| iCER | Intelligent Control by Exhaust Recirculation |
| LNG | Liquefied natural gas |
| MESDU | Mitsui E&S DU |
| OPEX | Operational expenses |
| PTO | Power take-out |
| TC | Turbocharger |
| VCR | Variable Compression Ratio |
| WiCE | WinGD integrated Control Electronics |

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## 10 CONTACT

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