Next-generation technologies to safeguard LNG-fuelled engine investments

2020

In uncertain times, how do ship owners and operators select the propulsion investments that will power their next generation of vessels through upcoming emissions targets?

For WinGD, the answer lies in advancing the reliability, efficiency and emissions performance of its engine platform, while building in the flexibility to operate on clean fuels. The latest advance in WinGD's dual-fuel X-DF engine platform precisely illustrates this drive.

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Introduction

While the use of LNG as fuel in marine engines has the potential to reduce shipping's greenhouse gas (GHG) impact, the emission of unburned methane from engines – known as methane slip – can compromise that reduction. As methane is the main component of LNG, any slip also represents wasted fuel. These two factors drove WinGD to seek better ways to minimise methane slip when it developed its second-generation X-DF technology.

Low-pressure two-stroke engines already offer benefits compared to both four-stroke engines, which have higher methane slip and GHG emissions, and high-pressure Diesel-cycle engines, which demand a more costly installation and cannot meet IMO Tier III NOx emissions in gas mode without aftertreatment. The NOx advantage will be particularly important as the North Sea and Baltic Sea introduce a NOx Emission Control Area from 2021, with further zones currently under discussion.

X-DF engines are ready to burn carbon-neutral synthetic or bio-derived LNG, without modification, when it becomes available – helping ship owners to meet IMO's GHG reduction targets.

There is potential to further improve performance as well as cutting NOx, methane and GHG emissions. This paper, originally presented during the Gastech Virtual Summit (7th September 2020), shows how a new technology improving combustion control on X-DF engines leads to a reduction in fuel-gas consumption of 3%, a reduction in liquid fuel consumption of up to 5% and a reduction in methane slip of up to 50%.

With these advances in combustion control, WinGD is both minimising the impact of using fossil-based LNG and preparing its engine platform for the efficient use of emerging clean fuels – making X-DF the ideal engine to power shipping through the energy transition and beyond.

Background

The low-pressure gas technology for low-speed two-stroke engines has come a long way since the start of development in 2011 by Winterthur Gas & Diesel Ltd. (WinGD). The low-pressure gas technology was selected by WinGD because it had proven to provide the highest benefits, especially regarding emissions, capital investment and maintenance costs. The first low-pressure low-speed two-stroke dual-fuel engine (an RT-flex50DF) was successfully type approved in 2015 and the first vessel entered service in 2016. The technology has been gradually introduced across the X engine portfolio under the engine type designation X-DF. The acceptance of the technology in the market is indicated by the increase in market share. As of July 2017, X-DF became the best-selling dual-fuel low-speed engine in the maritime market. There are over 315 X-DF engines for various vessel types on order and approximately 60 engines already in operation.

WinGD X-DF engines have become the standard choice for LNG carriers.

The emission characteristics of X-DF engines shown in Figure 1, are low in terms of nitrogen oxides (NOx), sulphur oxides (SOx) and particulate matter (PM) compared to other technologies as a result of the lean-burn Otto cycle combustion process. The carbon dioxide (CO2) emissions of X-DF engines are reduced compared to conventional engines because of the higher hydrogen-to-carbon ratio of natural gas in comparison to liquid fuels.

The low-pressure dual-fuel technology applied to X-DF engines has demonstrated to be a proven solution for high efficiency and for meeting Tier III NOx emission standards without the need of exhaust after-treatment systems.

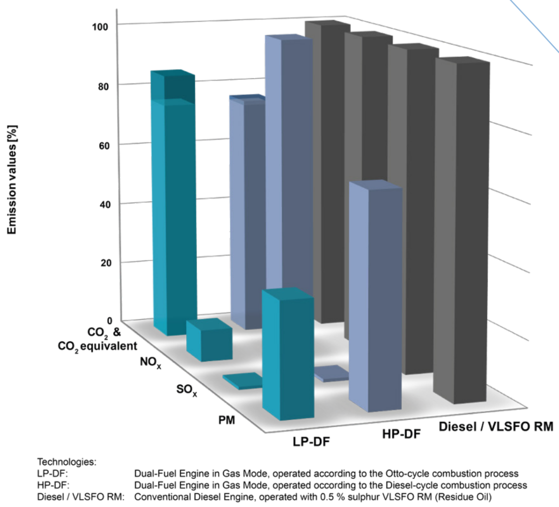


Figure 1: X-DF emissions characteristics

Now, extensive field experience collected has indicated that the technology offers opportunities for further optimisation in two areas:

1. An increase in the engine geometric compression ratio would lead to an increase of thermal efficiency both in gas and diesel mode operation;
2. The reduction of emissions of unburned hydrocarbons, mainly methane.

The introduction of an exhaust recycling system activated in gas mode - Intelligent Control by Exhaust Recycling (iCER) - has a positive influence on the thermodynamic parameters of the low-pressure dual-fuel engine and offers the possibility to increase thermal efficiency both in gas and diesel mode operation. Moreover, it has a positive influence on the unburned hydrocarbon emissions.

Technical details

Dual-fuel technologies

There are two basic dual-fuel technologies available for modern low-speed engines as seen in Figure 2. High-pressure dual-fuel low-speed engines operate on the Diesel cycle whereas low-pressure dual-fuel engines operate on the Otto cycle. In the Diesel cycle combustion process, the fuel-gas is injected at very high pressure via the cylinder cover and burned in a gas-jet flame ignited by pilot fuel. The combustion is locally rich. WinGD dual-fuel engines use low-pressure technology and operate on the Otto cycle. Fuel-gas is injected in the cylinder at low pressure via gas admission valves at the cylinder liner mid stroke. The lean fuel-gas/air premixture is then ignited by pilot fuel.

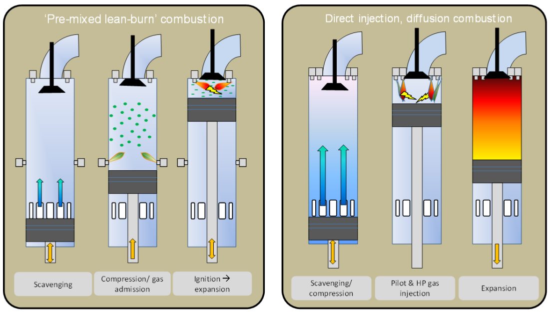


Figure 2: Otto cycle (left) and Diesel cycle (right) comparison

A low-pressure dual-fuel engine requires the correct homogeneous fuel-gas/air mixture - not too rich and not too lean – which should be evenly distributed within the whole combustion chamber. The optimal operating window of existing X-DF engines is shown in Figure 3. The area to the left of the rich limit indicates an over-rich fuel-gas concentration that could lead to higher combustion speeds and to auto-ignition (knocking).

The shaded area to the right indicates an increasing air/fuel-gas ratio which leads to an over-lean fuel gas concentration and consequently increases combustion instability as the mixture might not ignite. WinGD's X-DF technology ensures there is no immediate gas trip when crossing the reach limit or in case of an over-lean mixture, because the firing pressures, knocking and misfiring are constantly monitored, and the air/fuel-gas mixture controlled.

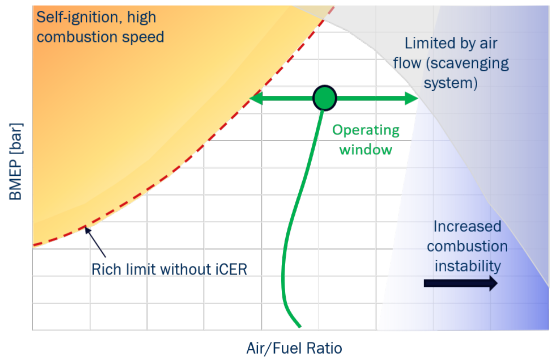


Figure 3: X-DF operating window - Air/fuel ratio versus brake mean effective pressure (bmep)

The application of the iCER system reduces the mixture reactivity by substituting part of the oxygen with cooled exhaust gas. The iCER system consists of a low-pressure exhaust recycling path including an efficient exhaust gas cooler (EGC) with neglectable contamination of cooling water due to clean fuel-gas and combustion. The extended operating window of X-DF engines with iCER is shown in Figure 4. The gas reactivity depends on the exhaust recycling rate and the air/fuel-gas ratio. By applying exhaust recycling, the premixed gas reactivity is reduced and, consequently, the ignition delay increases while the combustion speed slows down. An increased resistance to auto-ignition and the reduced combustion speed give the possibility to control the combustion phasing even at high loads and reduce the firing pressure. Hence an increase of the geometric compression ratio becomes possible which increases the thermal efficiency both in gas and diesel mode operation.

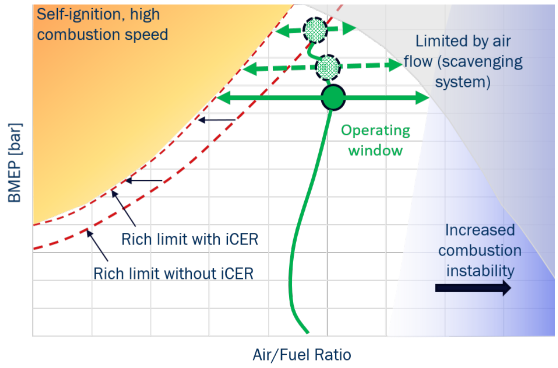


Figure 4: X-DF operating window with iCER

Thermodynamic aspects

The gas mixture composition changes as the rate of exhaust gas recycling increases. The influence is seen in Figure 5. As the percentage of recirculated gas increases, the amount of oxygen (O2) replaced by CO2 increases proportionately. The amount of nitrogen (N2) in the mixture is also slightly increased. Since CO2 has a higher heat capacity than O2, the peak temperature in the cylinder are reduced. Additionally, the lower O2 content in the scavenge air results in a reduction of the premixed gas reactivity which leads to an increase of the ignition delay and to a slower combustion speed. Consequently, increasing the exhaust gas recycling rate leads to smoother combustion.

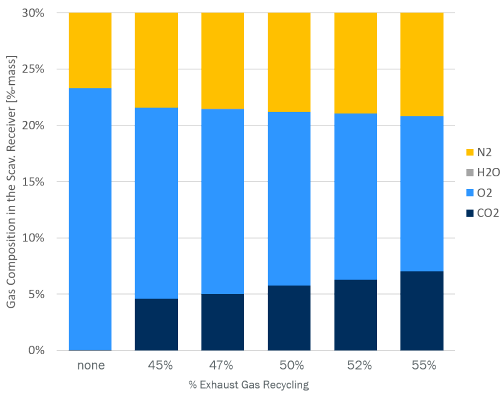


Figure 5: Influence of exhaust recycling on gas mixture composition (at 75% engine load

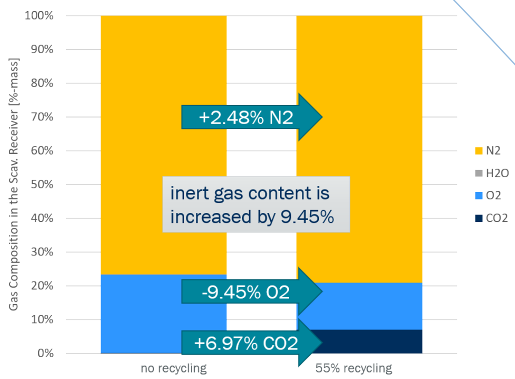


Figure 6: Change of gas composition by applying 55% exhaust gas recycling

The recirculation of exhaust gas into the engine increases the friction and results in a loss of efficiency. The known drawback on efficiency when applying exhaust recirculation to a gas engine is very low when running on a low-speed two-stroke engine because of the very small share of fuel-gas compared to the total mass. Specifically, the share of natural gas with a low isentropic exponent compared to N2 and O2 which have high isentropic exponent is small. The difference between a low-speed two-stroke engine and other applications is shown in Figure 7. On a passenger car engine, the isentropic exponent reduces by 0.01 when adding 30% exhaust recycling. On a low-speed two-stroke engine it reduces only by 0.0015 when adding 30% exhaust recycling. It can be concluded that there is minimal efficiency drawback of the gas composition when applying exhaust recycling on a low-speed two-stroke engine.

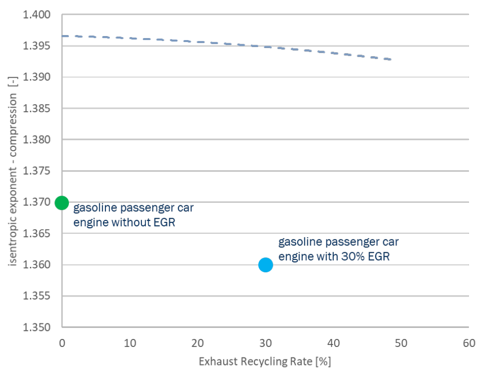


Figure 7: Isentropic exponent vs exhaust recycling rate

The small efficiency loss can be more than compensated for by an increase in the geometric compression ratio when applying exhaust gas recycling. For dual-fuel engines operating on the Otto cycle at lower compression ratios compared to similar engines operating on the Diesel cycle, a small increase in the compression ratio results in large efficiency gains. This is seen in Figure 8 which shows that increasing the compression ratio in the lower range of the horizontal axis, leads to high efficiency gains for dual-fuel engines.

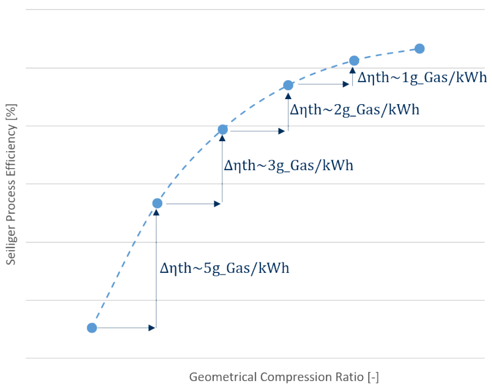


Figure 8: Efficiency vs compression ratio

As the exhaust recycling rate increases, the air/fuel-gas ratio (Lamda) decreases, as seen in Figure 9. Very high recycling rates are possible on low-speed two-stroke dual-fuel engines without lacking in oxygen for the combustion process. This is made possible by the turbocharger efficiency which enables a larger mass of air to be pushed through the engine and therefore regulate the amount of oxygen.

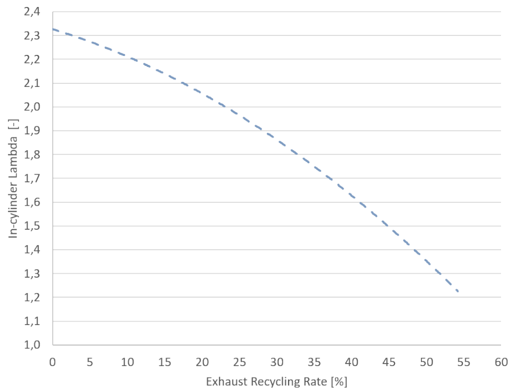


Figure 9: In-cylinder lamda vs exhaust recycling rate (%)

Specific methane slip emissions are inversely proportional to the exhaust gas recycling rate. When applying recycling, the methane (CH4) in the exhaust gas is divided into a recirculation path and a funnel path. Increasing the rate of recycling gives methane in the recirculation path a second chance to burn in the combustion chamber. Typically, a 50% exhaust recycling rate enables 50% of methane to burn again during the combustion. Consequently, the emissions of unburned hydrocarbons are reduced.

System description

The iCER is designed to cool and recirculate part of the exhaust gas through a low-pressure path during operation in gas mode. Compared to a high-pressure path, the main benefit is the ability to use the full turbocharger capacity. It is possible to recirculate exhaust gas up to a maximum rate of 50% mass flow. This is handled through a system adjacent to the engine that circulates part of the exhaust gas after the turbine through an exhaust gas cooler (EGC) to the compressor inlet. The exhaust gas and the fresh air are mixed before entering the compressor wheel of the turbocharger.

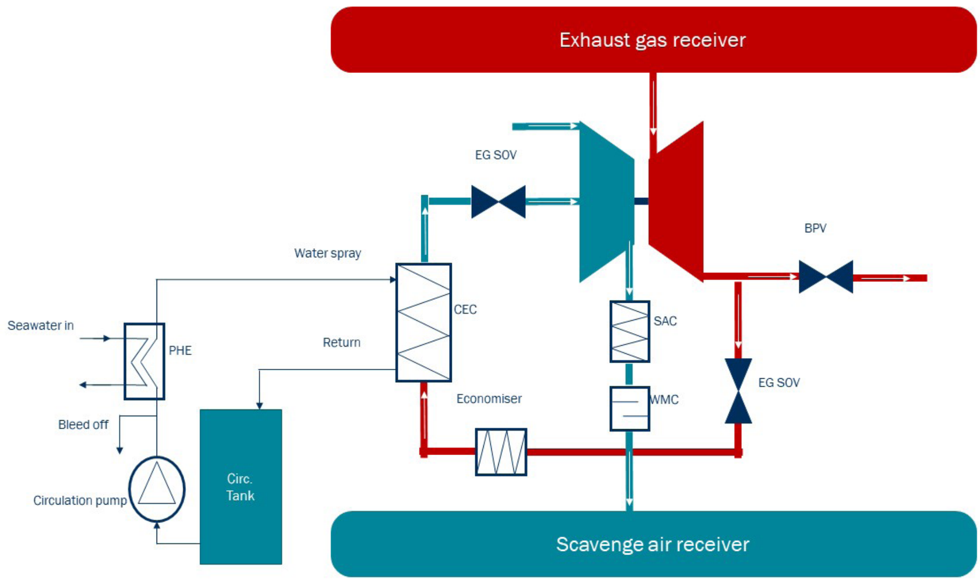


Figure 10: System overview

Abbreviations in Figure 10:

BPV	Back pressure Valve
CEC	Cascade Exhaust gas Cooler
SOV	Shut Off Valve
SAC	Scavenge Air Cooler
EG	Exhaust Gas
WMC	Water Mist Catcher
PHE	Plate Heat Exchanger

Arrangement

The iCER system is placed close to the engine as a stand-alone arrangement. An exhaust gas cooler and demister are installed as part of the system. The cooler tower contains two sections: the quench section and the absorber section. Hot exhaust gas enters at the top of the quench section which cools with water using spray nozzles at the top of the section. The exhaust gas then flows to the bottom of the absorber section which handles the main cooling.

The absorber section contains filler material functioning as an enlarged cooling surface with water introduced from the top. The demister finally removes any water in the exhaust gas.

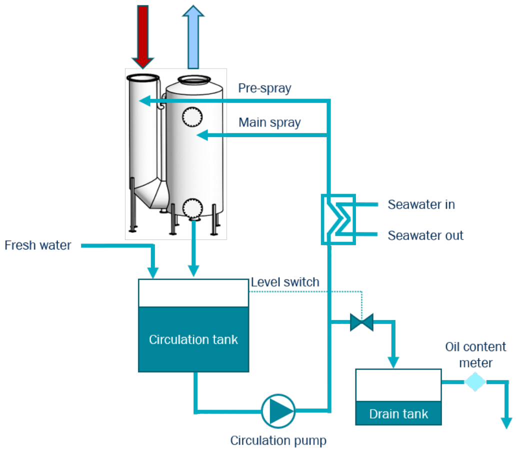


Figure 11: Arrangement of cooler, circulation water and drain

The cooling process reduces the temperature of the exhaust gas to below its dew point of ~40 °C. Below the dew point water starts to condense out of the exhaust gas which leads to excess water in the system. This is beneficial to avoid an increase of acidity in the recirculated water. The water used for cooling the exhaust gas is recirculated fresh water, stored in a circulation tank. The recirculated fresh water used in the exhaust cooler is cooled by sea water via a plate heat exchanger. The excess water generated by cooling the exhaust gas below its dew point is discharged to a drain tank and monitored continually by an oil content meter.

Waste heat recovery

To increase the total steam production, an optional economiser can be placed on the top of the jet tube (quench section) of the exhaust cooler. By applying a small economiser, the energy of the recirculated exhaust gas can be used. The economiser can be connected directly to the steam line.

The outlet temperature can be lowered to below 160-170°C because the exhaust gas is essentially sulphur free (iCER is active only in gas mode).

Figure 12:Arrangement of micro economiser (Source: Alfa Laval)

Performance improvement

The application of iCER technology to WinGD's X-DF engines brings several improvements in relation to gas combustion stability, fuel efficiency and emissions.

Gas combustion stability

With iCER technology, gas combustion can be fully controlled by adjusting the exhaust gas recycling rate and the pilot injection timing to optimise the fuel-gas consumption over the engine load range. Figure 13 shows the effect of increasing the rate of recycled exhaust gas (indicated by the arrow) while maintaining a constant pilot injection timing. The combustion speed decreases as seen from the shape of the curves and the peak cylinder pressure decreases. The recycling rate that results in the optimal combustion behaviour and improved fuel consumption is selected.

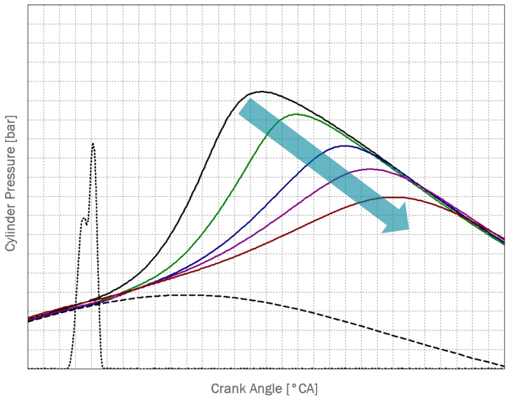


Figure 13:Effect on gas combustion by increasing recycling rate (at constant pilot injection timing)

The effect of adjusting the pilot injection timing while keeping a constant exhaust recirculation rate is seen in Figure 14. A delay in the pilot injection timing by a few degrees (indicated by the arrow) results in a slower combustion speed and reduced cylinder pressure. Therefore, the combustion can be controlled by means of the diesel pilot injection for optimal efficiency.

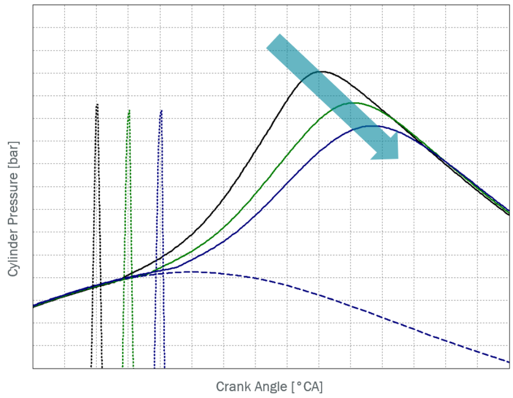


Figure 14: Effect on gas combustion by delaying pilot injection timing (at constant recycling rate)

Improved knocking control

Exhaust gas recycling enables better control of knocking. Figure 15 indicates that an increase of the recycling rate helps to reduce the amplitude and the fluctuation of knocking. The slower combustion speed made possible by applying iCER ensures that gas pockets in the combustion chamber are not igniting uncontrollably. The temperature in the cylinder after compression is lower and, consequently, the activation energy required to ignite any gas pockets is higher resulting in a less ignitable fuel-gas/air mixture.

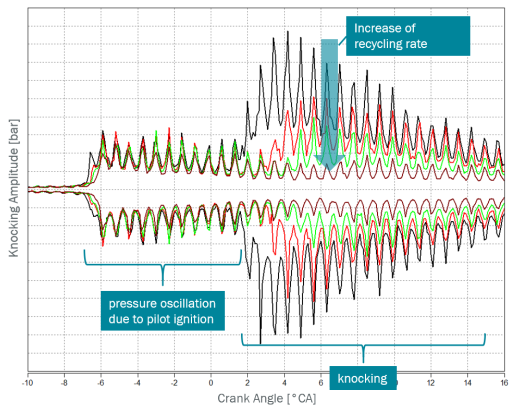


Figure 15: Effect on knocking by increasing exhaust recycling rate

Fuel consumption and emissions

As explained, the application of exhaust gas recycling and the improved combustion stability allow an increase of the geometric compression ratio (CR). Fuel consumption is decreased proportionately to the increase of CR, as seen in Figure 16. At high loads the thermal efficiency gain is lower compared to part loads because the maximum cylinder pressure is limited by the strength of the engine structure. Moreover, as the CR is increased the risk of knocking increases therefore the CR that represents the best compromise between efficiency (fuel consumption) and reduced knocking is selected.

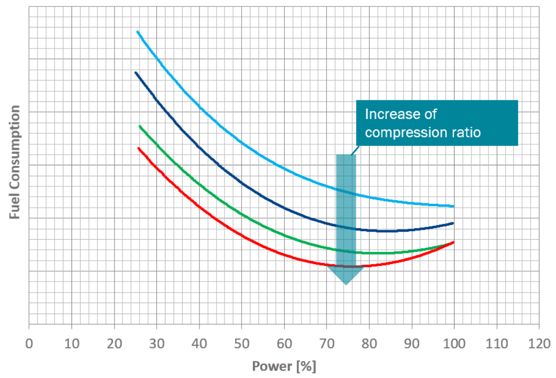


Figure 16: Fuel consumption improvement with increase of compression ratio

The iCER system has a direct benefit on the greenhouse gas (GHG) emissions of X-DF engines. The CO2 equivalent emissions are reduced with increasing compression ratio values. For X-DF engines with iCER the GHG emission footprint is reduced by 8% based on the selected compression ratio.

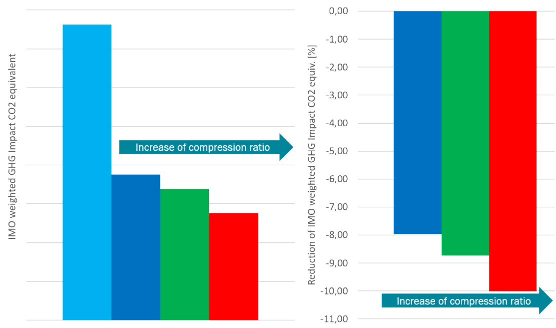


Figure 17:GHG emissions vs compression ratio (CR)

The emission characteristics of X-DF engines with iCER are seen in Figure 18. In addition to reduced CO2 equivalent emissions, the NOx emissions decrease by approximately 35% as a result of the lower peak temperature in the combustion chamber.

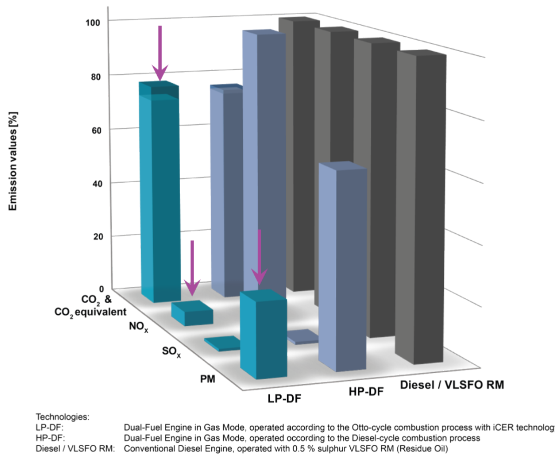
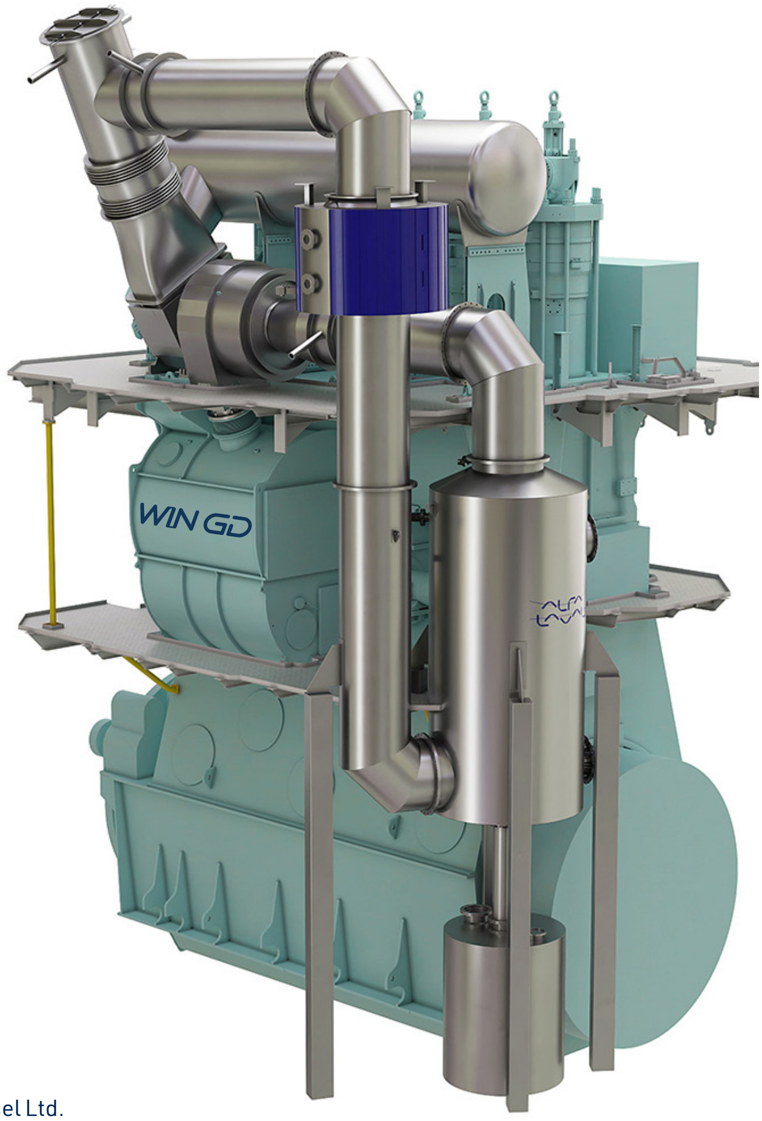


Figure 18: X-DF2.0 emission characteristics

Conclusion

The application of iCER technology to X-DF engines delivers enhanced combustion control through the use of inert gas. The main benefits of the technology are a reduction of energy consumption in gas mode by 3%, a reduction of fuel consumption in diesel mode operation by up to 5% and the reduction of methane slip of up to 50%. Further benefits include improved fuel-gas combustion stability and increased resistance to self-ignition, as well as reduced peak pressure variance and fluctuation. The iCER technology will be available for WinGD's entire X-DF portfolio.



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