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Radical derating as retrofit technology to reduce carbon impact from large 2-stroke marine engines

Retrofit Solutions

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This paper has been presented and published at the 31st CIMAC World Congress 2025 in Zürich, Switzerland. The CIMAC Congress is held every three years, each time in a different member country. The Congress program centres around the presentation of Technical Papers on engine research and development, application engineering on the original equipment side and engine operation and maintenance on the end-user side. The themes of the 2025 event included Digitalization & Connectivity for different applications, System Integration & Hybridization, Electrification & Fuel Cells Development, Emission Reduction Technologies, Conventional and New Fuels, Dual Fuel Engines, Lubricants, Product Development of Gas and Diesel Engines, Components & Tribology, Turbochargers, Controls & Automation, Engine Thermondynamis, Simulation Technologies as well as Basic Research & Advanced Engineering.

ABSTRACT

The increasingly stringent requirements imposed by the marine environmental legislation, such as the introduced Energy Efficiency Existing Ship Index (EEXI, calculation required for all ships) and the Carbon Intensity Indicator (CII), effective January 2023, are driving the market towards requests of increased engine efficiency and reduced greenhouse gas emissions. In this context, the demand of retrofit solutions for engines on field is growing and Wärtsilä is committed to ensure engine operation according to legislation and customers' requirements. Therefore, Wärtsilä Services Switzerland Ltd. has developed a radical derating solution, featuring modifications on the engine allowing fuel consumption reduction up to 14%.

Wärtsilä's project aims at providing customers with a solution allowing a radical decrease in carbon footprint and increase in engine's efficiency by reducing the engine's maximum power, reducing the engine's bore and optimizing the engine's operation to customers' current needs. The solution requires the replacement of the upper part of the engine, from the piston rod to the cylinder liner, from the piston to the cylinder cover and exhaust valve. In addition, new injectors are mounted, and the turbochargers are re-matched to the new engine power output.

In the present paper, the concept, the engine infrastructure, and results from the first conversions are presented. The discussion focuses on the whole retrofit process, from engine modifications to the combustion process, fuel consumption reduction and exhaust emissions. Moreover, particular attention is dedicated to the description of the engine conversion and the challenges connected with replacing large components on-board the vessel in addition to testing the "new" engine directly at sea.

In conclusion, the concept which has already being successfully tested on several large container vessels is thought to retrofit operating diesel engines, reducing their maximum power output to match the customers' required operating profiles and allowing a drastic reduction in fuel consumption and carbon emissions.

1 INTRODUCTION

The increasingly stringent requirements imposed by the marine environmental legislation, such as the introduced Energy Efficiency Existing Ship Index (EEXI) and the Carbon Intensity Indicator (CII) [1], effective January 2023, drive the market towards requests of increased engine efficiency and reduced greenhouse gas emissions (GHG), with the aim of reducing carbon intensity of all ships by 40% by 2030, and 70% by 2050, compared to 2008 levels [2]. In this context, the demand for innovative retrofit solutions to reduce the carbon footprint of existing fleets steeply increased over the last years, being shipping an important source of greenhouse gas emissions, almost 3% of the global CO_2 emissions [3]. Among the main measures to improve EEXI (measure of ship's energy efficiency in grams of CO_2 per ton and nautical mile) and CII (provides a rating to the ship based on its carbon emission intensity), it is worth to mention hull and propeller optimization, route optimization, after treatment systems (e.g.: scrubbers), adoption of alternative fuels, reduction of speed and of course increased engine efficiency. Practices for EEXI compliance are reported in [4], highlighting as most ship owners are already applying engine power limitation (EPL) to comply with EEXI.

As engine builder, Wärtsilä is committed to ensure engine operation according to legislation and customers' requirements. Wärtsilä Services Switzerland Ltd. has developed its radical derating solution (called Fit4Power) that extends the emissions-compliant lifetime of merchant vessels, featuring hardware and software modifications on the engine allowing a fuel consumption reduction up to 15%. The solution is highly attractive, allowing to extend the effective service life of a vessel and thus avoiding the necessity of building new vessels, which is extremely expensive and produces more carbon emissions than retrofitting existing ones.

2-stroke engine radical derating is a technology that modifies large marine engines to operate at lower power outputs than their original design. Wärtsilä's solution provides customers the possibility of achieving a strong decrease in carbon footprint and increase in engine's efficiency by reducing the engine maximum power and bore size, increasing the compression ratio and maximum in-cylinder pressures, re-matching the turbochargers (TCs) and optimizing the engine's tuning and operation to the customers' needs. In fact, following the global financial and economic crisis of 2008, shipowners and charterers started reducing the average ship speed to cut fuel consumption and therefore, operational costs. As a result, especially the biggest engines (e.g.: Wärtsilä RT-Flex96C-B) became too powerful and not optimized for the new market demand. The Fit4Power solution allows an optimization of heat losses with a smaller combustion chamber designed to achieve the reduced engine power output. By significantly reducing the engine's operational power range, radical derating improves fuel efficiency and reduce emissions, aligning older vessels with modern environmental standards. This method leverages existing hardware, avoiding the need for complete engine replacement, and presents an economically viable pathway to decarbonization for shipowners. The solution includes the replacement of the upper part of the engine, from the piston rod to the cylinder liner, from the piston to the cylinder cover and exhaust valve. In addition, new injectors are mounted, and the turbochargers are re-matched to the new engine power output.

In the present paper, the concept, the engine infrastructure and results from the first conversions are presented. The discussion focuses on the whole retrofit process, from engine modifications to the challenges connected with testing the "new" engine directly at sea, from the combustion process to the fuel consumption and exhaust emissions reduction.

2 WÄRTSILÄ'S FIT4POWER SOLUTION

Over the last decade, the operating strategy of vessels has undergone significant changes due to the increase in oil prices. In order to reduce the total fuel consumption of merchant ships, ship owners and charterers have adopted the strategy of reducing the vessels' operating speed, which in turn reduces engine operating power output and results in a trade-off between shipping time and cost. The reduction in engine operating power has determined a situation where most of the large bore low-speed 2 stroke engines in the market operate at very low loads (well below 50% of their original maximum power output), resulting in poor engine efficiency. The Fit4Power solution is offered to customers through an extensive project requiring extreme collaboration and synergy within the company's departments. The project includes multiple phases, from the investigation of the technical solution through 1D and 3D computational fluid dynamics (CFD) simulations to design of components, from discussion with classification societies and flag state to procurement of components (including availability and lead time), from the preparation of the new engine control software and tuning to the preparation of the onboard campaigns. In addition, discussions with suppliers (e.g. TC maker) are required to guarantee that all components are delivered on time while communication with shipyard must be managed to secure a precise scheduling of all the activities during the preparation and execution of the engine conversion. The conversion is typically carried out during an already planned dry-dock, since its extent doesn't allow to easily carry on the hardware modifications during commercial operation. In addition, often the engine conversion is coupled with a replacement of the propeller to achieve a better propulsion efficiency in the new (reduced) engine power output range. Though, this option is not required by Fit4Power, since the converted engine can operate on the original nominal propeller curve, as reported in Figure 1.

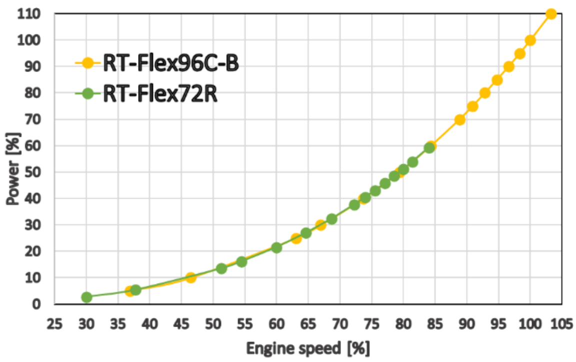

Figure 1. Engine before and after conversion operating on the same nominal propeller curve.

The engine conversion is followed by a commissioning of the entire system and the sea trial, which lasts for a few days and includes the testing of the derated engine and its fine tuning to secure the contracted fuel benefit and, at the same time, the compliance with exhaust emissions. Finally, upon collection of data, a detailed report (NOx technical file) is sent to the involved classification society for approval.

Moreover, each project, having about 7 months lead time, requires a detailed risk management for possible costs overrun, supply chain disruption, last minute changes in the vessel schedule, components delivered out of specification, just to mention a few of the multiple challenges that could possibly be faced.

For each conversion, it is necessary to organize the required Wärtsilä service teams, including superintendents, engineers and mechanics for:

- disassembling of the existing components
- assembling of the new cylinder units and other engine related components
- removal and replacement of turbochargers / turbocharger components
- installation of required new piping, such as cooling water pipes
- installation of new engine control software
- continuous quality checks and control of each work step.

To develop the solution, around 12000 engineering hours were required and 850 drawings were prepared or updated before the first conversion, carried out during the second half of 2022 (sea trial completed on October 19th). From that milestone, more than 10 conversions have been completed and many others are in progress / order. With this solution, Wärtsilä offers to customers requiring the conversion of their 2 stroke RT-Flex96C-B engines to RT-Flex72R, a customized product allowing the selection of the best maximum power output, based on engine's real life load profile and guarantee an efficiency improvement up to 15% (up to 2000 tons of fuel per year), decreased OPEX through fuel and service costs reduction and a significant reduction in CO_2 emissions (up to 6400 tons per year). As a result, the vessel lifetime is prolonged, its CII compliance extended by 3 to 5 years and shipowners get some breathing space before the adoption of alternative fuels to keep their fleet compliant with (future) regulations.

In Figure 2, the achievable fuel benefits at different power outputs are shown. To demonstrate the benefits of Fit4Power, a reference measurement campaign before the engine conversion is carried out and, at agreed engine loads, all the relevant performance parameters, in addition to exhaust emissions, are recorded and used later as reference values to prove the contracted savings. Values in Figure *2* are achieved with the solution featuring the replacement of turbochargers with brand new ones.

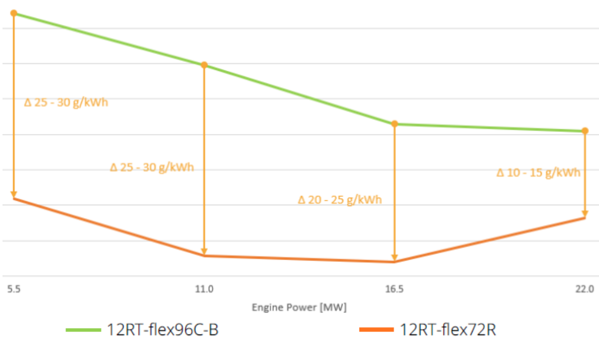

Figure 2. BSFC reduction achievable with Wärtsilä's Fit4Power.

3 ENGINE CONVERSION

The solution is providing a complete new engine from the stuffing box upwards while the engine lower part stays unchanged. In addition, a brand-new series of turbochargers or new turbocharger matching is required.

Table 1 reports the list of the main engine components being replaced while Table 2 lists the main steps to be performed during the engine retrofit. In addition, a clear sequence of the conversion is reported in chapters 3.1 and 3.2

Table 1. Main engine components to be replaced

Piston and Piston Rod
Cylinder Liner
Cylinder Cover
Exhaust Valve
Stuffing Box
Compression Shim
Hydraulic Pipes
Lubrication System (pumps, pipes, quills)
Fuel Injectors
Injection Control Unit
Piping (fuel, cooling water, drain, etc.)

Table *2*. Main steps during the engine retrofit

Disassembly of original engine components
Assembly of new engine components
Installation of new TCs / re-matching of existing TCs
Integration of Piping
Installation of electronic components including the new Wärtsilä engine control software
Final checks and commissioning

3.1 Removal of components from the Wärtsilä RT-flex96C-B engine

From the original engine (Figure 3), the whole cylinder unit, highlighted in orange in Figure 4 and including piston rod, piston, liner, cylinder cover, and exhaust valve together with the injectors and injector control unit is removed while the exhaust valve control unit is modified to fit the new requirements of valve actuation.

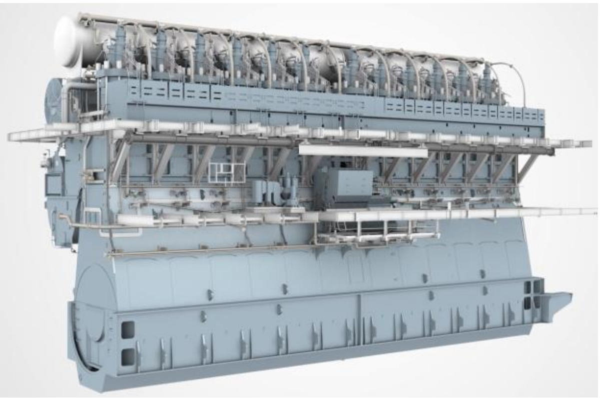

Figure 3. RT-Flex96C-B engine.

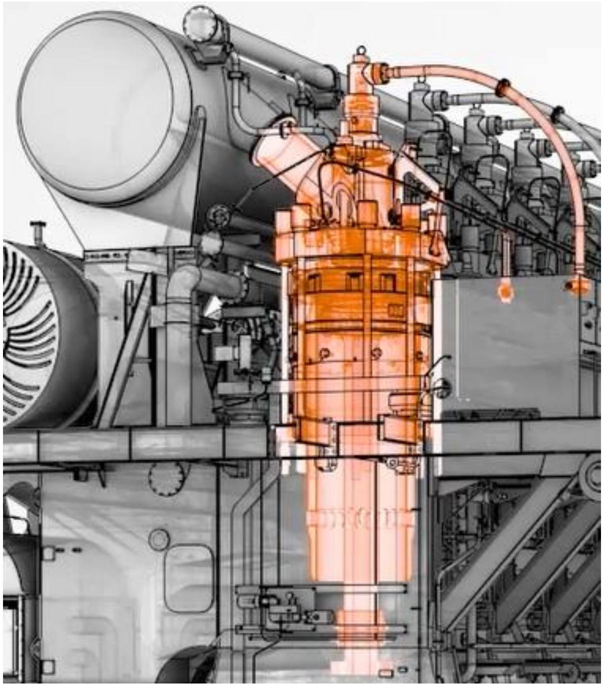

Figure 4. Cylinder unit.

Once the whole upper part of the engine is completely dismounted, the remaining structure appears as reported in Figure 5.

Figure 5. Engine’s status after dismantling the RT-Flex96C-B components.

3.2 Assembly of the Wärtsilä RT-flex72R engine

The assembly of the de-bored cylinder units would start introducing the new liner with adapter piece, piston, piston-rod and stuffing box in the original engine structure (Figure 6). The new cylinder liners feature a complete re-design of the intake ports to optimize the air flow at higher compression ratio. In fact, while the original RT-Flex96C-B engine is characterized by a compression ratio of 17, the retrofit solution allows values as high as 24. Moreover, the new components (liner, cover, piston) are engineered according to modern design principles to withstand higher stresses and are certified for firing pressures up to 200 bar (while for the original engine, a maximum of less than 150 bar was allowed). The increased in-cylinder pressure levels are not causing any issues to the original bearings because of the reduced bore (piston surface) determining, at fixed pressure, a reduction in force (p=f/s). Afterwards, the new cylinder cover, with exhaust valve, and injectors would be fitted (Figure 7), followed by new fuel injector pipes connected to the injection control unit (ICU), hydraulic pipes and modified valve control unit (VCU), all reported in Figure 8. Once the main components are installed, lubrication pump and pipes plus integration of piping for cooling water, leakage and starting air are connected (Figure 9).

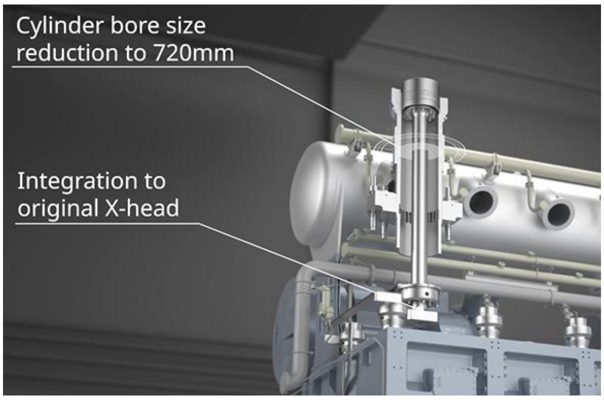

Figure 6. Schematic of the new cylinder liner with adapter piece, piston, piston rod and stuffing box being inserted in the original engine structure.

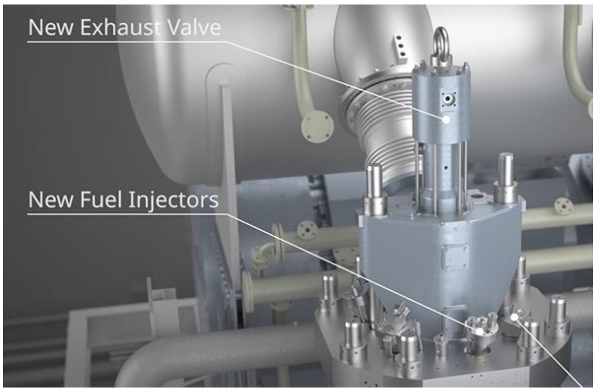

Figure 7. New cylinder cover, with exhaust valve, and injectors.

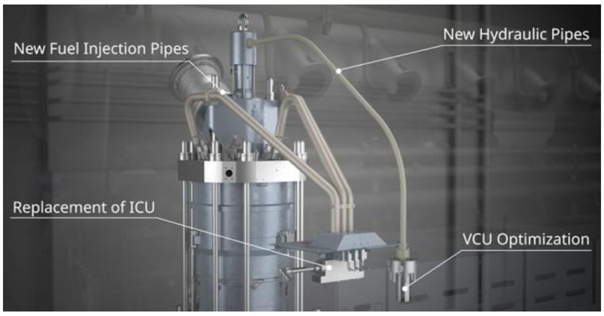

Figure 8. New fuel injector pipes connected to the ICU, hydraulic pipes and modified VCU.

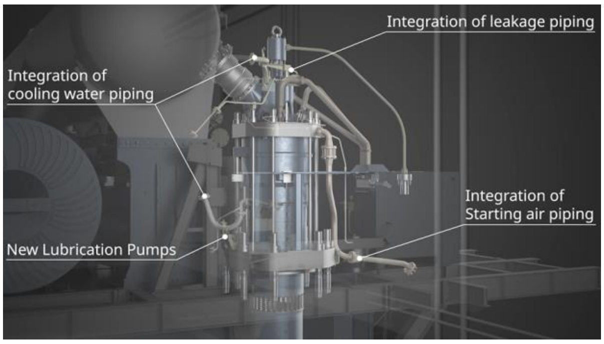

Figure 9. Lubrication pump and pipes plus integration of cooling water, leakage and starting air piping.

After the exhaust valve is connected to the exhaust manifold through an intermediate piece and all the heat insulating material is placed, the new cylinder block is completed (Schematic reported in Figure 10). On the other side of the engine, new turbochargers are connected to the intake and exhaust systems. It is worth highlighting that the original engine, depending on the number of cylinders, features 2, 3 or 4 turbochargers. With Fit4Power, instead, only 2 units would remain active while the others (if any) would be removed and the corresponding pipes permanently blinded. Since replacing the turbochargers with new ones is a quite expensive exercise, the alternative is the re-matching of the existing ones, together with sequential TC operation. In this way, only one TC is engaged at the low / medium loads while the second TC is activated only for the high loads. This solution, though, offers sub-optimal results in terms of achievable fuel benefits and is often not the preferred one by customers. For this reason, the present discussion focuses on the solution including 2 brand new turbochargers, both operating in the whole load range. The selection of the proper turbocharger is a cooperation activity carried out with the TC maker to achieve the highest efficiency, a surge margin above 10% in the whole load range and a margin towards the TC maximum allowed speed at 100% engine load.

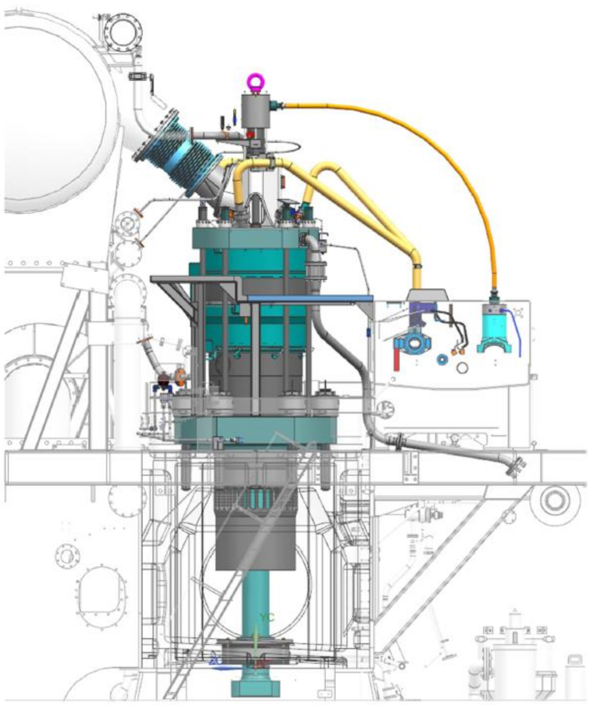

Figure 10. Schematic of one of the new cylinder units re-assembled and completed.

4 PERFORMANCE OF THE RETROFITTED ENGINE

The present chapter focuses on the performance of the retrofitted engine, focusing on the comparison with the original one, not only in terms of fuel efficiency and exhaust emissions but even looking at the in-cylinder pressure traces at a fixed power output and other engine relevant parameters.

To introduce the chapter, it is worth highlighting as the engine's displacement is almost halved with the retrofit solution, leading to higher brake mean effective pressure (BMEP) values and reduced engine friction and heat losses (reduced surface), which, in turn, determines improved fuel consumption. In addition, the reduced engine displacement requires smaller turbochargers, due to the decreased in-cylinder mass flow rate. Installing brand new TCs (state of art) allows reaching higher scavenge air pressure levels (increase up to 80%, depending on the engine load), with the positive effect of increasing the in-cylinder trapped mass which, together with the increased compression ratio, allows achieving higher compression and firing pressures (increase up to 100%, depending on the engine load), thus increased engine efficiency. As an example, Figure 11 and Figure 12 report the comparison between in-cylinder pressure traces before and after the engine conversion. The curves refer, respectively, to an engine load of 40 and 80% of the new maximum engine power output, which is reduced by around 55% compared to the original one. In the specific case, the engine's compression ratio was increased from 17 to 24 and the scavenge air pressure, thanks to the new turbocharger matching could be increased by 0.85 bar at 40% load and 2.2 bar at 80% load.

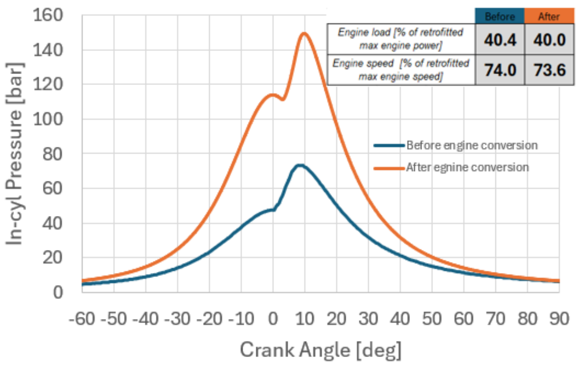

Figure 11. In-cylinder pressure comparison at 40% load – before vs after conversion.

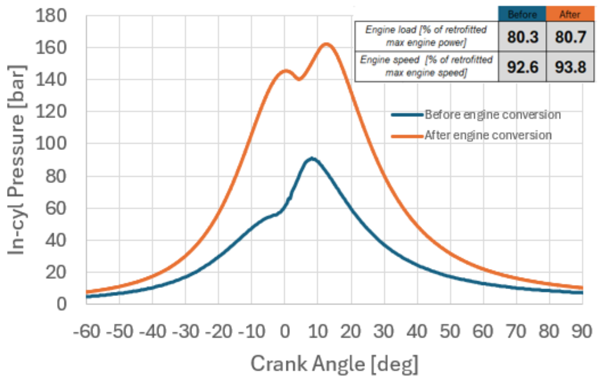

Figure 12. In-cylinder pressure comparison at 80% load – before vs after conversion.

The increase in compression ratio (with respect to the original configuration) results to be not only propaedeutic to higher in-cylinder pressures but also favourable towards avoiding increase of NOx emissions. In fact, the reduction of NOx emissions with increased compression ratio and fixed firing pressure, is an experimentally proved trend within 2-stroke diesel engines.

As already mentioned, to demonstrate certain fuel savings, two measurement campaigns are carried out, a reference campaign before engine conversion and the sea-trial after conversion including engine optimization and final measurements. This because measurements on a test bench are not possible being the RT-Flex96C-B no longer a portfolio engine (no new builds sold anymore). The necessity of optimizing the engine directly at sea leads to additional difficulties. For example, keeping a constant load during measurements might be challenging in case of adverse weather conditions and / or traffic at sea. In addition, customers are usually very demanding about having the vessel back in service as soon as possible. Therefore, a detailed test planning and multiple working shifts are required.

In specific projects, where the requested new power output, compression ratio and injector nozzle tip angles were never tested before, an extensive testing campaign after conversion might be necessary. It includes the installation (only for the duration of the sea-trial) of instrumented components, to measure the temperature of the hot parts (piston, liner, cover and exhaust valve) and verify that it is not exceeding the limits. In particular, the temperatures of piston and exhaust valve (moving components) are acquired via telemetry, allowing faster installation and measurement. In addition, through a dedicated acquisition system, in-cylinder pressure traces, exhaust valve opening and closing profiles and injection profiles are continuously monitored and acquired. To complete the extensive measurement equipment, a certified exhaust analyser is installed to measure NOx, CO, CO_2, and O_2 at the engine's exhaust and make sure the retrofitted engine is compliant with the relevant IMO limit; lambda sensors are installed at the exhaust of the cylinder units and various pressure and temperature sensors allow monitoring the major engine and turbochargers parameters.

Once the test campaign at sea is complete, an official sea-trial is executed and witnessed by customer and a class surveyor. The compliance with NOx emissions is then certified in the NOx technical file, prepared by Wärtsilä's testing team and reviewed, accepted and stamped by the classification society. In addition, contracted fuel consumption benefits are documented and sent to the customer in an additional dedicated report.

4.1 Discussion of results from one of the converted engines

In the present section, performance results of a specific 12-cylinder RT-Flex96C-B engine are discussed to show a concrete example of benefits coming from Fit4Power. Firstly, Figure 13 shows the comparison, at fixed engine power output, of BMEP before and after the conversion. The difference is given by the reduced engine bore, from 960 to 720 mm while the engine stroke stays unchanged.

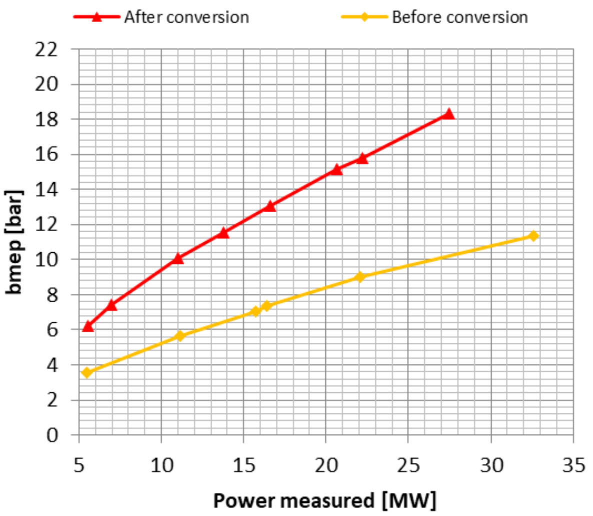

Figure 13. BMEP before vs after engine conversion.

After the engine conversion, an extensive re-tuning is required. The new tuning is preliminary prepared with the GT-Power 1D simulation tool while fine tuning is required onboard to achieve the targets in terms of BSFC and NOx. Figure 14 and Figure 15 report, respectively, the variation in exhaust valve closing, which determines the effective compression ratio and the different injection timing. For both parameters, quite a different trend (in addition to the absolute values) is visible, confirming the necessity of a substantial re-tuning after the application of Fit4Power. In addition, exhaust valve opening timing and injection pressure are re-tuned as well.

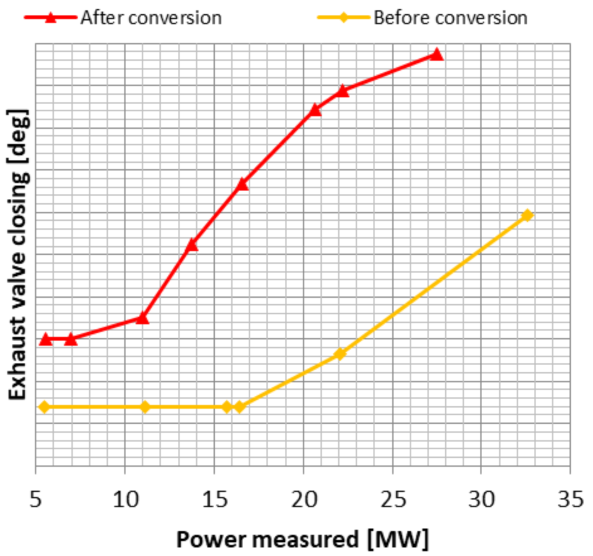

Figure 14. Exhaust valve closing tuning before vs after engine conversion.

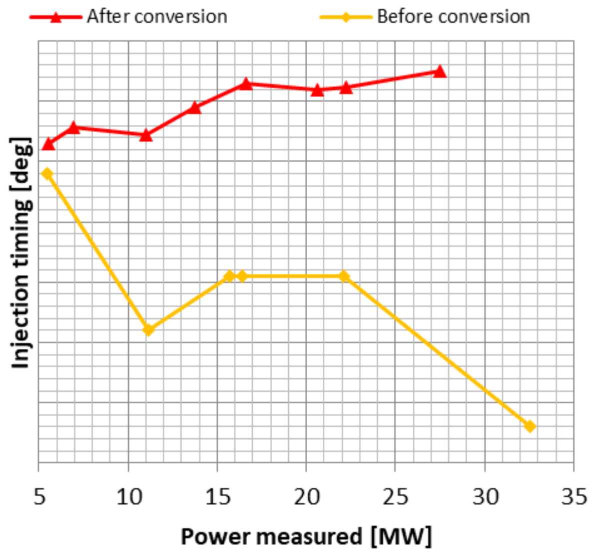

Figure 15. Injection timing tuning before vs after engine conversion.

As previously mentioned, Fit4Power requires substantial modifications on the turbochargers side. Figure 16 reports the operating curve after conversion on the new compressor map. As visible, the turbocharger matching was properly carried on, since the operating points are correctly positioned and allow achieving a sufficient TC maximum speed and surge margin and operating, at the same time, in (or very close to) the area of maximum efficiency in the compressor map. The scavenge air pressure at maximum engine load reaches, after conversion, a value of about 4.7 barA, being this the typical maximum value of modern turbochargers for 2 stroke engines. The increase in scavenge air pressure with respect to the values before conversion is significant and is shown in Figure 17. It is worth to highlight though, that the scavenge air pressure trend reported for the engine before conversion case (yellow curve) does not reach the maximum achievable value, being the new maximum engine power output less than 50% of the original one. For the engine before conversion, at maximum power output, the scavenge air pressure was reaching a value of around 4.1 barA.

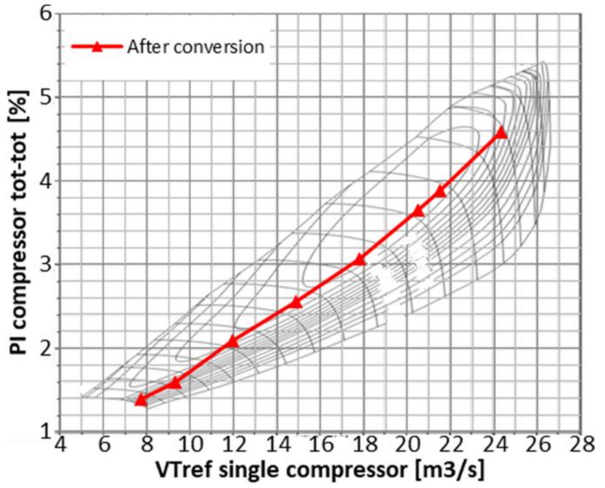

Figure 16. Operating curve within the compressor map.

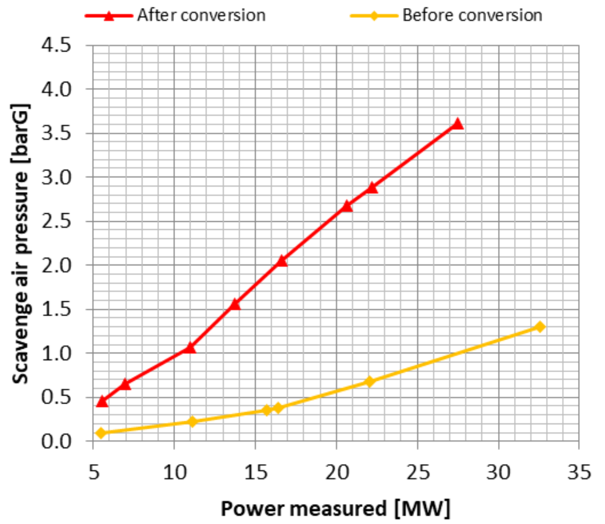

Figure 17. Scavenge air pressure before vs after engine conversion.

The discussed increase in engine compression ratio, together with the new turbochargers and new tuning, determined a significant increase (up to 80 bar) in both end compression pressure (Figure 18) and maximum in-cylinder pressure, reported as “firing pressure” (Figure 19). The increased values are withstandable because of the design of the liners and covers allowing pressures up to 200 bar.

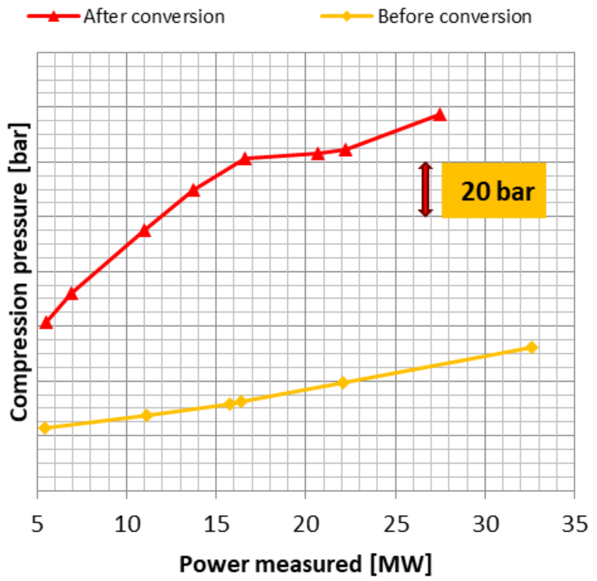

Figure 18. Compression pressure before vs after engine conversion.

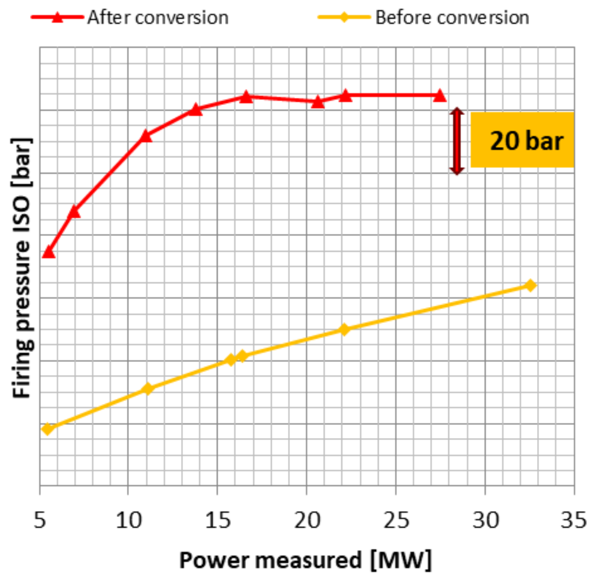

Figure 19. Firing pressure before vs after engine conversion.

As a result of the new hardware and software, the achievable benefits in terms of brake specific fuel consumption are huge, up to 30 g/kWh at low loads and above 15 g/kWh in most of the load range. The fuel saving trend, achieved on a specific installation, is reported in Figure 20. In addition, Figure 21 provides some numbers related to potential annual fuel savings and CO_2 emissions savings. At the different engine power output conditions, it is visible how the fuel reduction could reach up to 3000 tons per year while the CO_2 reduction could exceed 10k tons per year. The reported values are calculated at each power output, considering that the ship would keep the load constantly and throughout the whole year. The values in Figure 21 are reported only for reference and to provide an order of magnitude. Instead, to establish a more precise fuel consumption and CO_2 reduction (in tons per year), the specific real engine load profile has to be considered.

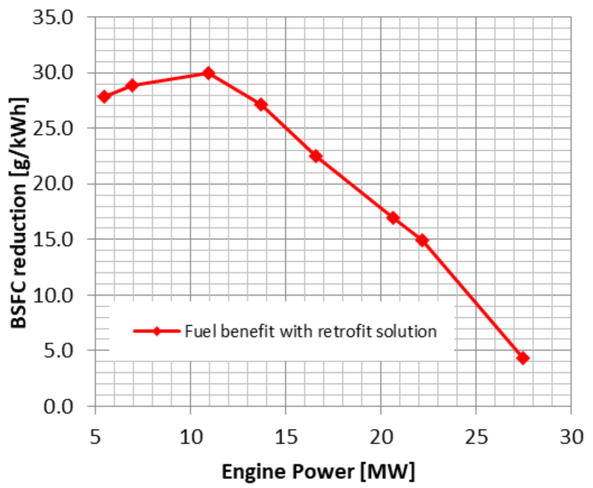

Figure 20. Brake specific fuel consumption reduction with Fit4Power.

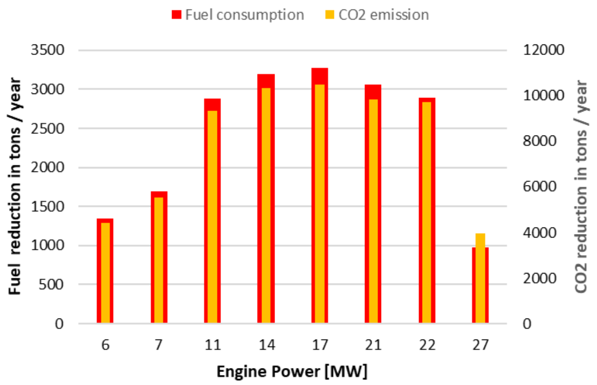

Figure 21. Tons per year of fuel and CO_2 emission reduction with Fit4Power.

To conclude the present section, dedicated to the discussion of engine performance, it is worth to mention that the achieved benefits were accomplished even keeping the engine compliant with the IMO NOx limits, Tier II in the specific case. In fact, the final NOx average weighted value was kept 2.2 g/kWh below the applicable limit.

5 CONCLUSIONS

Over the last decade, the operating strategy of vessels has undergone significant changes due to the increase in oil prices. In order to reduce the total fuel consumption of merchant ships, owners and charterers have often adopted the strategy of reducing the vessels' operating speed, which in turn reduces engine power output and results in a trade-off between shipping time and cost. The reduction in engine operating power has determined a situation where most of the large bore low-speed 2 stroke engines in the market operate at very low loads, resulting in poor engine efficiency.

To address the issue and reduce both the carbon footprint and total fuel consumption (thus contributing to a more sustainable shipping industry) of merchant vessels powered by the RT-Flex96C-B engines, Wärtsilä Services Switzerland Ltd. has developed a retrofit product including de-boring and de-rating of the engine, resulting in improved engine efficiency and reduced CO_2 emissions.

The original engine top part components (from the piston rod and upwards) are dismantled during a planned dry-dock and replaced with new and state of the art ones, resulting in the most extensive retrofit project ever conducted by Wartsila Services Switzerland Ltd. Once the engine conversion is completed (from the original 12RTflex96C-B to the new 12RTflex72R), a phase of commissioning followed by the engine re-tuning and final sea-trial is carried out. All in all, once the vessel is ready to sail, in about a week the engine is commissioned, tuned and handed over to customers. After that, a new engine certification is released by the specific classification society upon receiving and approving the new NOx technical file. The sea trial test campaigns have confirmed, for all executed conversions, the expectations of significant fuel consumption and CO_2 reductions. The achievable benefits in terms of brake specific fuel consumption are up to 30 g/kWh and above 15 g/kWh in most of the engine load range. With the achieved BSFC reduction and engine load profile provided by multiple customers, it has been calculated that up to 2000 tons of fuel and 6400 tons of CO_2 can be saved per year of operation.

6 DEFINITIONS, ACRONYMS, ABBREVIATIONS

BMEP: Brake Mean Effective Pressure

BSFC: Brake specific fuel consumption

CO: Carbon monoxide

CO_2: Carbon dioxide

CII: Carbon Intensity Indicator

CFD: Computational fluid dynamics

EEXI: Energy Efficiency Existing Ship Index

EPL: engine power limitation

GHG: greenhouse gas emissions

IMO: International Maritime Organization

ISO: International Organization for Standardization

ICU: Injection control unit

MARPOL: International Convention for the Prevention of Pollution from Ships

NOx: Nitrogen oxides

O2: Oxygen

OPEX: Operating expense

TC: Turbocharger

VCU: valve control unit

1D: mono-dimensional

3D: three-dimensional

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9 CONTACT

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