Wärtsilä journey for two stage turbocharging: 4-stroke medium speed diesel engines

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Abstract: Nowadays internal combustion engines are facing demanding requirements: on top of everything the emissions restrictions and the request of reliable efficiency. The increase of air flow density to combustion chamber made by two stage supercharging, is on top among solutions to limit pollutants coming from thermodynamic cycles.
This paper shows some step of the Wärtsilä way to develop a reliable two stage turbocharging system for 4-stroke medium speed diesel engines, for Marine and Energy markets.
Journey starts from early 2000's with first laboratory investigations, till to current serial production and future studies. Wärtsilä two stage engines have remarkable levels of compact and proven design, providing outstanding performance results with high efficiency levels, that at the same time allow compliancy to stricter emission regulations.
As a general overview, good OPEX levels are provided to Customers by efficient maintenance concepts and high safety levels. Some mentions will be provided around design and testing processes, with focus on engineering to fit two stage assembly on engine structure and on product validation. Extensive laboratory experience, together with known market applications, can provide a collection of field experiences about two stage, these results are source to increase knowledge and setting new and higher targets to current products, also in relation with incoming decarbonization process and future fuels.

Key Words: two stage turbocharging, efficiency, emissions, reliability, validation, field experience, decarbonization, engine, turbocharger

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1 Introduction

Manufacturers of combustion engines for Marine and Energy sectors are requested to be compliant to stricter combustion's emission levels. Technology needs to adapt to the way opened by Green Deal. Recently, focus is on NO_x (Nitrogen Oxides), and how to drastically reduce that as a result of combustion. If environment protection is on top of everything, the basic demands of engineered products are still reduced fuel consumption (efficiency) and optimized maintenance schedule (reliability). Wärtsilä is striving for all these: this paper will describe a part of this engineering effort.
Chapter 2 explains why two stage turbocharging can assure the increase of air flow density to combustion chamber, and why this is needed as a technique to limit pollutants, resulting from thermodynamic cycles; those cycles today are enhanced with introduction of extreme Miller effect, this last can effectively face the NO_x formation.
Chapter 3 shows the main steps of Wärtsilä in the field of two stage turbocharged engines developed for Marine and Energy markets. Journey starts from early 2000's with first laboratory investigations, till to current serial production with W32TS, W31 and W46TS; and hint of general data and about main application of case study two stage engines will be described.
When describing design process in the detail, chapter 4 will show how Wärtsilä two stage engines can reach remarkable levels of compact design, providing outstanding performance results with high efficiency levels and easy maintenance requirements. Process includes also structural and fluid dynamic calculations, leading trough deep testing and validation process, to components, subassemblies, assemblies and engines with good OPEX levels. About performance tuning, turbos matching is efficient when existing together with other technologies, such as variable inlet and exhaust valve closing, and electric air and waste gates.
Extensive laboratory experience with many collected running hours, together with feedbacks from market applications successfully delivered, can provide a collection of field experiences about deployed two stage engines. In chapter 5 will be seen how these results are source to increase knowledge and to enhance design of future products.
Proven that two stage turbocharging is an effective solution to reduce NO_x emissions, there is still CO_2 as pollutant from combustion of fossil fuels with key effect on global warming, so decarbonized fuels are needed: chapter 6 will give a view on how Wärtsilä is already on the way to develop engines running on such named future fuels, like ammonia, hydrogen and methanol. Those influence performances and turbos, this also need to be deepened.
The reader will have clear evidence that the process to release a new technology on an engine, is not simply end-to-end, but can be defined like a circular path where new requirements set new limits, and new challenges rise from the need of a better or new technology, in the aim of continuous improvement, environmental protection and market behavior.

2 Why two stage turbocharging?

Turbochargers are known for capability to increase power density of internal combustion engines, together with higher efficiency of thermal unit.
Another fundamental result of charge air inlet pressure increase, it's the effect on combustion cycles, with the aim to reduce pollutants by limiting environmental impact of burned fuels.
This chapter will briefly list why NO_x emissions are considered dangerous and how they are limited by legislations, and will demonstrate effectiveness of Miller cycle, knows also as Miller effect or Miller timing, in reducing NO_x formation, and why a two stage system is needed for that.

2.1 NO_x emissions, limited by legislations

Combustion process of fuel, at defined ranges of temperatures and oxygen concentration in the engine, is the originator of NO_x formation.
NO_x are nitrogen oxide (NO), nitrogen dioxide (NO_2) and nitrous oxide (N_2O); currently the existing majority are NO (~95% of total NO_x) & NO_2.
Together the NO and NO_2 are referred as NO_x, and main chemical reactions for their formation are based on oxygen high temperature combustion, when considered major than 2000 Kelvin:

$$O + N_2 \rightarrow NO + N$$
$$N + O_2 \rightarrow NO + O$$
$$N + OH \rightarrow NO + H$$

Environmental effects of NO_x are defined as belonging to acidification, when nitrogen oxides and sulphur oxides are responsible for acid rains generation, to eutrophication, known as over-fertilization, which negatively affects bio-diversity both on land and coastal waters, and to ozonification, given that NO_x contributes to formation of ground-level Ozone, which damages vege-tation, human health and contributes to global warming together with CO_2.
Industries and engine manufactures are driven in their daily operation by legislators, also in relation with NO_x: when referring to Marine engine appli-cations, IMO (International Maritime Organization) and US-EPA (Environ-mental Protection Agency) are the rulemakers; when looking at Energy (Power plant engine application), the constraints basis are provided by Ger-man TA-luft and by EU Industrial Emissions Directive (IED) 2010/75/EU.
More in detail, IMO released the "International Convention of the Provention of Pollution from Ships" known as MARPOL 73/78, and inside this, the Annex VI "Regulations for the Preventions of Air Pollution from Ships" sets the limits for NO_x and SO_x into engine exhausts. In the Annex VI there are 3 levels for NO_x defined as g/KWh based on engine speed: IMO Tier I applies to ships built from 1st January 2000 till to 1st January 2011, IMO Tier II reduced limits of Tier I by 20% and it's applied to ships built after 1st Janu-ary 2011.

IMO Tier III is taken in force from 2016: it's applied only in selected navigation areas ECA (Emission Controlled Areas) and reduces NO_x emissions of Tier I by 80%. ECA are beloging to North American and Caribbean coastal areas, plus European North and Baltic seas.
Following figure 1 provides an immediate view of IMO Tiers levels.

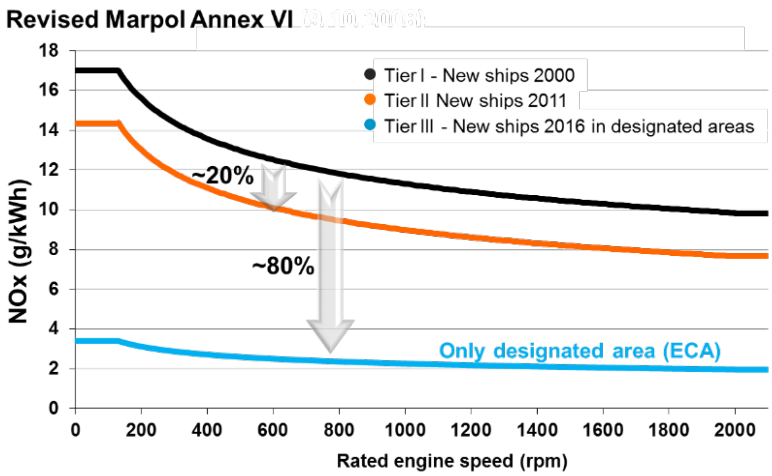

Figure 1: MARPOL Annex VI NO_x emission limits (source: Wärtsilä)

When referring to Energy (Power plant) generation units, instead, the German TA-luft sets NO_x limits for engines running all around the World as 500mg/Nm^3 at 5% O_2 dry; commonly also the stricter Half TA-luft (250mg/Nm^3 at 5% O_2 dry) is widely applied.
EU-IED Directive is even more strict: Gas engine NO_x limit is 75mg/Nm^3 at 15% O_2 dry; wheter liquid fuel engine limits are: 100..300 mg/Nm^3 at 15% O_2, depending on the plant size.
Following table 1 gives a summary of limits coming from previously listed regulators, expressing of all them as g/kWh. For the reader is easy to imagine how big is the engineering effort to be compliant with those, and how large is the variety of engine applications and solutions related to these challenge, more about all of these will be found in chapter 4.

Table 1: overview of NO_x limits as defined by legislators

Legislator	**NO_x g/kWh**
IMO Tier I	12.52
IMO Tier II	10.10
IMO Tier III	2.50
TA-luft	~ 1.20
Half TA-luft	~ 0.60
EU-IED 2010/75/EU	~ 0.50 ÷ 2.00

2.2 Technical principles for NO_x reduction

NO_x emissions can be mainly reduced by means of measures acting on combustion cycle and to its parameters, targeting to lower combustion temperature. Engineers so needs to focus on fuel and on charge air.
Of course, exhaust gas post treatment is also a solution, but this will not be deepened in this paper.
Given that NO_x formation is provided by high temperature combustion process, characterized by a "torch" combustion where the flame front is quickly propagating at 2000K or more, where exactly the flame edge is at so high energy to speed up the formation of nitrogen oxides. That's the reason why the engineering target is to reduce combustion temperature.
Solution for this is to realize a "pre-mixed lean burn" combustion with aim of low peak temperature with a uniform combustion propagation instead of a rapid flame front. So, when acting on fuel dynamics is possible to work on fuel injection by means of retarded injection, on optimized and different spray patterns or by focusing on fine tuning of fuel injection strategy with shaping of injection rates.
Contemporarily when focusing on charge air flow, the solutions to lower temperature are charge air cooling, Exhaust Gas Recirculation (EGR) and Miller timing, defined by Wärtsilä as Miller cycle.

2.2.1 Miller cycle

In 1950s Ralph Miller presented the charge air cooling by early closing of charge air intake valve (US Patent 2817322): when inlet valve is closed before piston bottom dead centre BDC, the total compression work will decrease. In other words, the result is a lower combustion temperature than the nominal one obtainable with a complete intake and compression cycle. Reduced compressions work means obviously and increased engine efficiency.
Ralph Miller's target was to increase engine output power, so the brake mean effective pressure BMEP, without exceeding the thermal and mechanical limits of the engine. Tens of year later, this low temperature combustion concept became the heart, when facing NO_x formation and their limitation.
Significant NO_x reduction is so assured by extreme early closing of charge air inlet valve: since intake period is shortened, high boost pressure is required to provide enough charge air into combustion chamber.
Summa summarum, pushing forwards for more anticipated inlet valve closing, means that where single stage turbocharged is not enough, the solution is a two stage turbocharged system.
An example is provided in figure 2, where is possible to notice the effect of earlier inlet valve closing, represented in X-axis. The red line, right Y-axis, draws NO_x reducing trend when anticipating inlet valve closing; whether the black curve, left Y-axis, sets the needed charge air over boosting (PIC), with reference to ambient pressure, required at maximum engine output power with constant injection timing and firing pressure.

Extreme reduction of NO_x requires and extreme increase of charge air boosting.

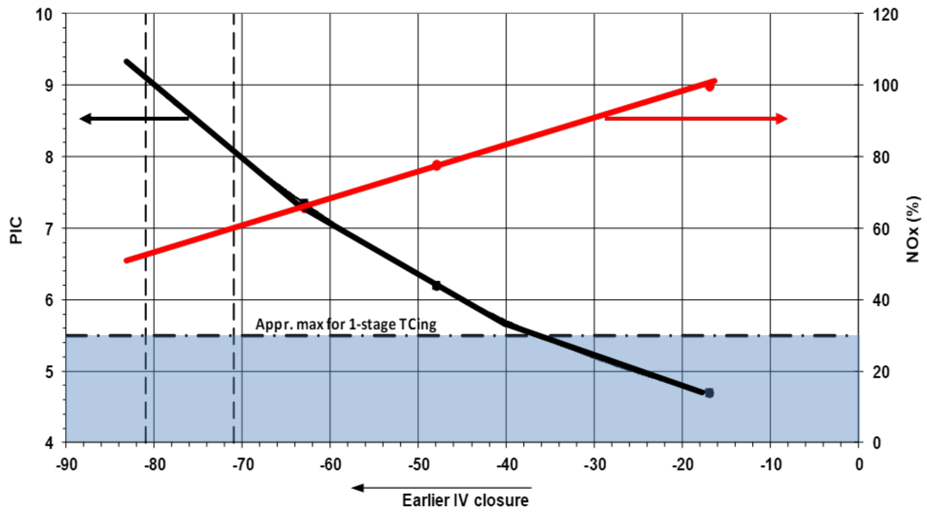

Figure 2: reduction of NO_x and increase of PIC with earlier inlet valve closure (source: Wärtsilä – W6L20)

Among Wärtsilä 4-stroke engine range of single turbocharged stage, the compression ratio of ambient air can reach values of PIC up to around ~ 5.8, an example of this has been described by Wärtsilä [1] for the case studied of W46DF engine that uses the a single stage turbocharger providing very high compression ratios (i.e. as high as 5.8 as above mentioned), at high turbocharging efficiency (i.e. 68%), combined with wider compressor maps among those of similar size turbochargers.
To overtake that already high PIC value, two turbos are then needed, and engineering processes need to strive for that.
Miller effect is remarkably appreciated when running engine with Otto cycle, when burning natural gas as fuel with driven ignition by means of spark, or preinjected limited quantity of liquid fuel. In Otto cycle main risks are misfire and knocking, but with a fine and correct tuning of excess air ratio (lambda), is possible to reach high delivered power together with high efficiency. This air excess ratio needs to be continuously tuned and driven during engine running, based on engine boundary conditions and on internal combustion parameters, especially during transient phases that are most at risk for knocking and miss firing occurrence.
Unfortunately, the available window for excess air ratio definition is narrow, as can be a seen in figure 3.
Miller helps engine technicians by enlarging this tuning window as described in figure 4, and allowing an easier control of engine combustion, means that more extreme is the Miller, wider is thermodynamic range of combustion process allowing easier tuning and best performances towards higher thermal efficiency. This gain is known as knocking margin gain, and even if demonstrated to be effective for Otto Gas combustion, similar advantages are of course beneficial also with other fuels.

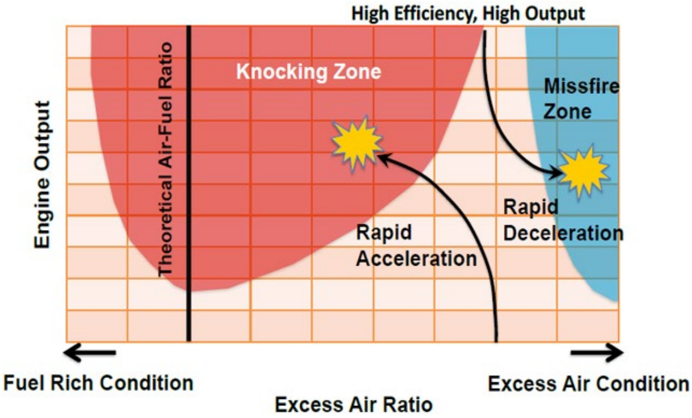

Figure 3: excess Air Ratio (lambda) vs knocking and misfiring zones, targeting high output (source: Wärtsilä).

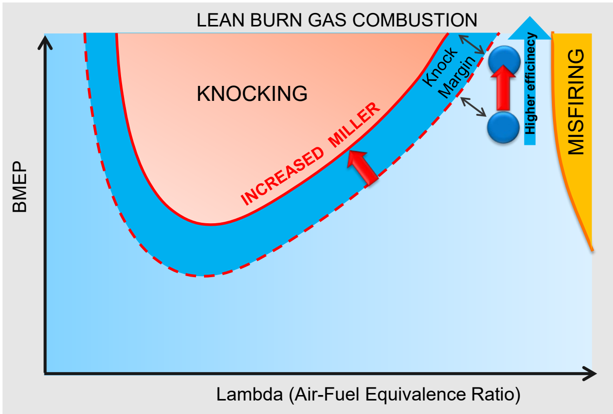

Figure 4: the effect of extreme Miller on knocking margin (source: Wärtsilä).

3 Wärtsilä two stage steps of last 20 years

Two stage turbocharging as a technical development to allow extreme Miller effect, is on the table of Wärtsilä engineering departments since almost 20 years. After the potential of two stage turbocharging was proven in NO_x reduction by the concept studies made in the early 2000s', the first tests with advanced Miller timing were run in 2006. Targets were to reduce Specific Fuel Oil Consumption (SFOC), to reduce NO_x, to increase engine output and to reduce derating when running engine out of standard ambient conditions. Since that time, many engines were tested, and the process included research, performance development, verification, design and component validation. As overview, detailed description of experiences up to 2015, briefly reported in this chapter, can be found in [2], whether latest steps are specific topic of this paper.

3.1 Single Cylinder Engine

To conduct deep development, a Single Cylinder Engine (SCE) was built in Wärtsilä premises. SCE testing allowed a detailed parametrization of combustion's results, when running extreme Miller, helping the tuning of two stage engines running at the same time in engine laboratory.
All basis, targets and results described in section 2.2.1 of this work, were clearly demonstrated: limits and gains for knocking margin targeting highest BMEP were mapped in detail; bottom dead center lower compression temperature was confirmed, like as the lower combustion temperature.
More than this, the turbocharging system efficiency increase up to 5%, allowed by PIC ratio increase, were calculated and measured, as can be seen in figure 5 here below.

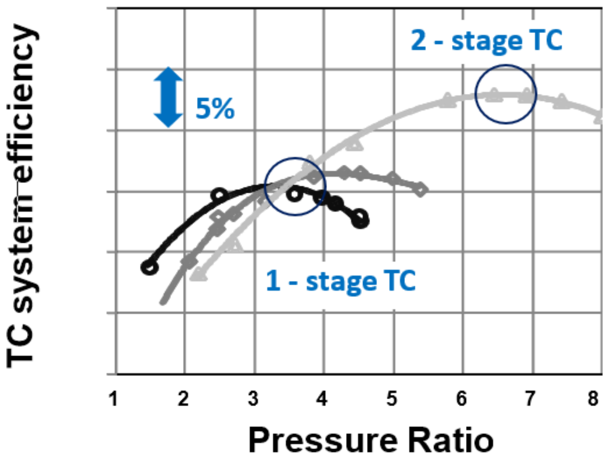

Figure 5: TC system efficiency increase with higher PIC (source: Wärtsilä).

3.2 Initial phase: W20 and W32

First full-size tests were carried out on a Wärtsilä 6L20 diesel engine.
The two stage system was designed just for testing purposes and was built by installing a separate turbocharger close to existing single stage engine.
Trials were held between 2006 and 2012, reaching in total 2100 running hours, those demonstrated the benefits of Miller timing and two stage turbo, when aiming for NO_x reduction.
Based on W20 experience, in November 2007 it was decided to design and build a production two stage version of the 20-cylinder W32 Power Plant engine (W20V32TS). Laboratory engine started in May 2009, clearly showing a reduction of both NO_x and SFOC.
Once designed, the W20V32TS looked compact in design, as can be seen in figure 6, just slightly bigger than a single stage turbocharged engine, even if number of turbos, charge air coolers and relative connections have been doubled.

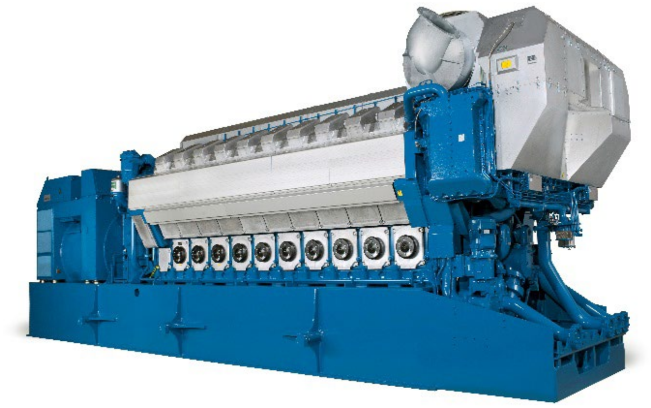

Figure 6: W20V32TS (source: Wärtsilä).

W20 and W32 provided excellent results, such: an output increase in the range of 13÷15%, overall turbocharger efficiency increased up to 10%-points, SFOC was reduced of 7÷9 g/kWh, and a NO_x reduction up to 50%. In general, the added charge air flow mass compared to single stage one, assured a thermal load within limits, also with engines running in hot ambient conditions.
Results also provided some development paths, such the need for a fine tuning of inlet valve closure and a precise tuning of turbosystem by means of waste gates, to manage engine load acceptance and partial load running behavior.
Focusing on turbochargers themselves, when comparing to a standard turbo used on single stage platform, it was clear that the high-pressure turbo HPTC needed lower air flow and lower pressure ratio, this to achieve maximum efficiency; the low-pressure turbo LPTC, instead, confirmed the traditional design but with a bigger air flow.

3.3 Intermediate phase: large bore studies

Moving further than great results achieved on W20 and W32, Wärtsilä focused efforts on biggest bore size in his product range, the W46.
The six cylinder version, named than W6L46F-TS was chosen and a project started with aim to improve the already good results earlier achieved, and to deepeen even more the overall knowledge of two stage products. Final design was proven to be compact and not heavily affected by added weight of additional components, in respect to structural dynamics.
Figure 7 provides a glimpse on this engine.
Turbosystem's studies confirmed the need for exhaust waste gates and air bypass; wheter inlet valve closing management was realized thanks to well known Wärtsilä VIC technology, see [1] for more reference.
Laboratory activities were held from 2012 to 2015, 2000 running hours were completed, and good results were proven: maximum PIC around 10

was achieved, total TC effficiency above 77% allowed a NO_x reducton up to 30%, by assuring also low thermal load compared to single stage version. On this engine was also possible to get more experience by running some exhaust treatment devices, such Selective Catalytic Reduction (SCR) and EGR.

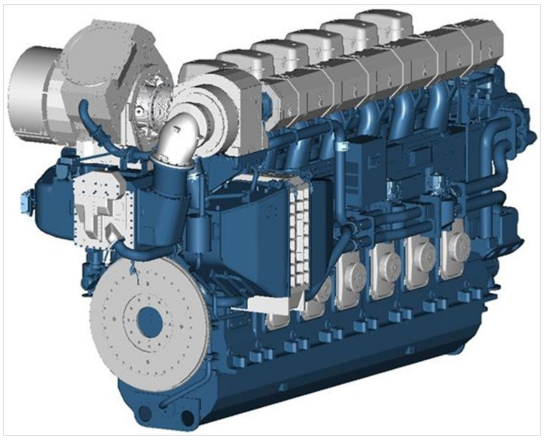

Figure 7: W6L46F-TS two stage large bore (source: Wärtsilä).

3.4 Current production: W31 and W46TS

Today, the first engine among Wärtsilä product range, that has all cylinder configurations equipped with two stage turbo systems is the W31. Wärtsilä W31, figure 8, represents a new generation of medium speed engines, designed to set a new benchmark in efficiency and overall emissions performance; all gained experience of above paper's sections has been utilized to make this outstanding engine.
The Wärtsilä 31 is the most powerful in its class with specific output of 610 kW/cylinder and is available in the range from 8 to 20 cylinders. In 2015 Wärtsilä W31 has been recognized by Guinness World Records as the world's most efficient 4-stroke diesel engine, with the best fuel economy of any engine in its class, it is available as pure diesel, Dual Fuel (DF) and Spark-Ignited Gas (SG).
Through high power output per cylinder, it enables a smaller footprint and cost-efficient installation. The two stage solution allows to be IMO Tier III compliant both when operating on pure natural gas, and with an SCR when using diesel liquid fuel.
Engines are delivered to Customers since 2017.

Figure 8: W31 (source: Wärtsilä).

Officially launched on 26th April 2022 [4], the W46TS is the latest engine of Wärtsilä family, manufactured only with two stage turbocharging system. Figure 9 provides an overview.

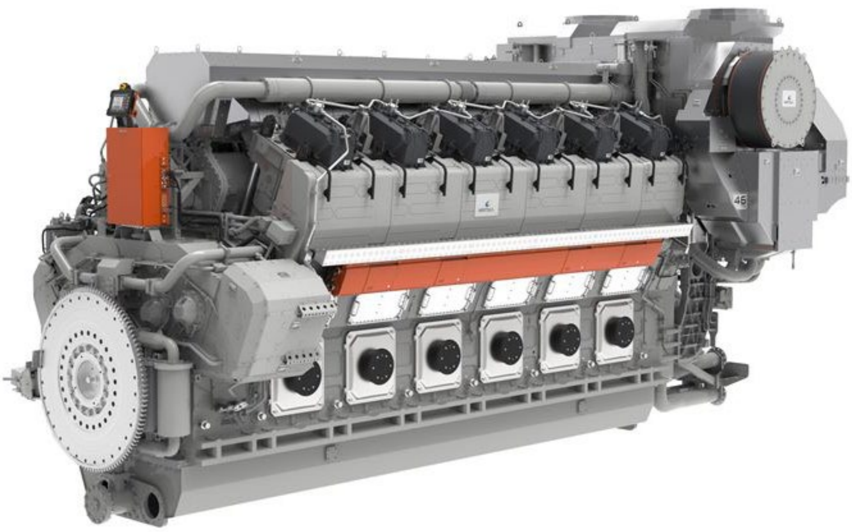

Figure 9: W46TS (source: Wärtsilä).

W46TS represents the next generation of medium-speed engines with best-in-class fuel efficiency and emissions performance with Future Proof fuel flexibility.
With a power of 1300kw/cyl, in the range from 7,8 MW to 20,8 MW, together with less cylinders than a same bore size but single turbocharged, this new engine has the highest power to weight ratio in its market. Benchmarking also demonstrates that, when running in 100% gas mode, the highest

efficiency measured is 52%, and, thanks to embedded combustion technologies, CO_2 emissions and methane slip are remarkably low: IMO Tier III is met.
Figure 10 represent the outstanding efficiency result achieved.

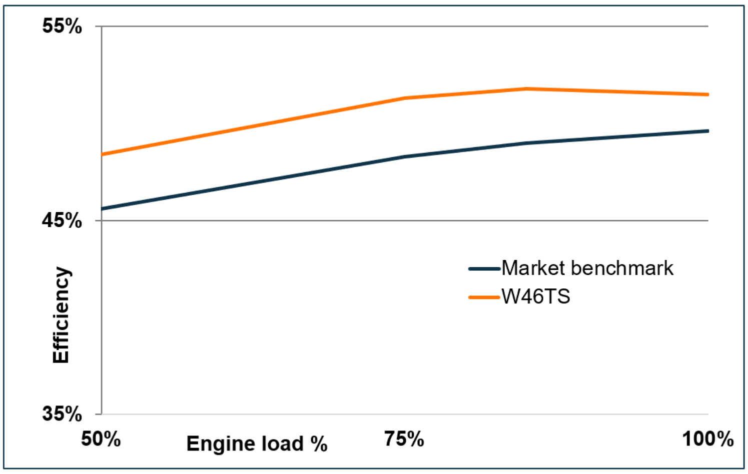

Figure 10: market benchmark for W46TS efficiency (source: Wärtsilä).

About turbocharging unit, in figure 11, the system has been tuned for highest efficiency and provides extremely high compression ratio for this size of engines. Low rotor inertia for fast engine loading, robust and reliable design with longer lifetime than current products, has once again set new limits.

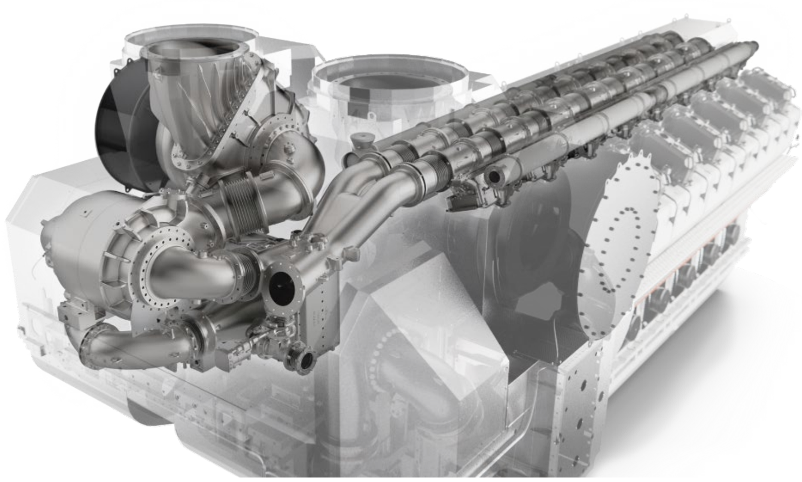

Figure 11: turbocharging group of W46TS (source: Wärtsilä).

4 Engine design principles for two stage turbocharging

Initial testing carried out 2006, with off-engine two stage turbocharging concept, was useful to understand limitations and cost structure of the separate system.

Two stage turbocharging system on engine. The target is to reach a compact design and dimensions by building turbocharging components on the engine. The main principles for the design and layout of two stage turbocharging have been clear and consistent from the beginning. Twice as heavy as one stage turbocharging system but feasible with smart design.

Design philosophy have been developed since 1990's using the latest design and calculation methods validated on engines in laboratories and in field installations. Target of engine design is to have material in correct locations for stiffness required by dynamics. The approach enables engine weight as light as possible contributing the improved engine efficiency and the lowest engine cost structure.

4.1 Design

Two stage turbocharging design philosophy is developed from experiences gathered from one stage turbocharged engines. Proven single stage turbocharging engine designs confirmed calculation principles and now used on development of two stage turbocharging systems.

It was noted during the first design process for two stage turbocharging system that compactness is beneficial for reliable product. Compactness is the key driver of engine dynamics. Design target: 1. Stay close to one stage turbocharging outline dimensions, 2. Gravity centre of turbocharging system near the engine block.

The first serial production engine utilizing two stage turbocharging system, W20V32TS, was developed from well-proven W32 engine. W32TS for diesel power plants was convenient start for world of two stage turbocharging due limited engine speed range applied in energy production. Engine genset natural frequency tuning was performed successfully, and positive operation experience more than decade gathered so far.

Important detail of two stage turbocharging system design is handling of increased pressure forces. Reaction forces after the high-pressure compressor and before the high-pressure turbine create significant stresses on pipes and ducts and on high-pressure charge air cooler frame. Air duct and exhaust pipe designs require careful consideration of boundary conditions and materials to avoid crucial design mistakes.

Thermal management with integrated insulation between the engine and turbocharging system create safe concept for the engine operation throughout the engine lifetime without risk for engine fire.

The service concept developed during the engine design targeted unsophisticated procedures for components requiring cleaning e.g., low-pressure charge air cooler. Removal of low-pressure charge air cooler do not need removal of surrounding components. High-pressure charge air cooler is mounted inside turbocharger bracket as service interval seen longer than low-pressure charge air cooler. The second reason for high-pressure charge air cooler location inside turbocharger bracket is pressure forces. Insert CAC side plate do not require special attention as pressure forces not affecting the frame. Standstill washing, without air cooler removal, is additional feature lately developed and released for even more convenient air cooler service.

Turbine washing optimization with CFD is current standard for two stage turbochargers shortening validation time.

4.2 Calculation

Calculation and virtual validation enable shortened engine development time. Development of calculation tools have given possibility to integrate design and calculation processes. Virtual validation is the utilization of simulations in the design process which enables the best quality at the best price in the shortest time. Simulations made early in projects drive design decisions up-front which reduce cost of changes and increase quality of the design.

Two stage turbocharging system increase loading on several areas of the engine leading to increased number of simulations. Coupling of the engine system models enables simulation of the engine using realistic loading. Design is updated in real time with calculation results to fasten time needed for design iterations. Integration have given possibility to remain and in the best-case speed up new product introduction time to market.

Dynamic optimisation is main interest area when developing new engine concept with two stage turbocharging system. Solid finite element model of new engine can be created, before the first prototype, in accuracy giving understanding about the system frequencies and modes. Finite element also offers tool to understand what can be done for engine design in case dynamic problems with the engine. Experience have shown ways to use engine components as mass damper for further optimising engine dynamics and lowering vibration levels over the speed range. Experience have also guide us for understanding how to reach cost savings with active and passive natural frequency tuning.

Pressure loading for component require understanding safety factors which needs to be applied for different materials under direct pressure loading. Reaction forces are, in many cases, divided between surrounding components to lower stress level for single component with design features.

Explosion analysis confirm the highest-pressure level which component can withstand without exceeding material elongation limit. Explosion analysis is used to prove component feasibility for dual fuel engine classification, safe operation in ships, without need for additional safety devices on engine.

4.3 Performance

Performance developments concentrate fine tuning of two stage turbocharging system simulation models. The first turbocharger matching trials were time consuming for optimum turbocharger specification.

Engine simulation, understanding influencing factors have guide us to situation where two stage turbocharging matching for new cylinder configuration or power stage is completed in few days during engine factory acceptance test changing nozzle ring, diffuser or nothing. Turbocharger service concept support rapid matching process. E.g., nozzle ring change with proper tools is possible in few hours on hot engine.

Two stage turbocharging have negative influence on loading performance as described earlier. Thermal mass and volume need to be heated up for proper engine response. Inertia’s have been lowered in various components e.g., turbines. In addition, development path has been introduction of faster and more accurate control valves (waste gate, by-pass) and changes on engine control.

4.4 Validation

Extensive testing and validation give Wärtsilä full confidence in the reliability of the new two stage turbocharged engine portfolio.

Current two stage turbocharging system mechanical validation do not require more than single stage turbocharging. Performance validation depends on time possible to use for finding optimal solution. Nature of two stage turbocharging give opportunity for endless number of freedoms to find even better engine performance concept.

Cleaning, during engine operation, is one of the key areas of two stage turbocharging concept validation. Fouling is affecting more to engine performance than on 1-stage turbocharged engine. Laboratory and field engine validation have been used for optimal cleaning parameters for acceptable performance level between mechanical cleanings.

5 Experiences with two stage turbocharging

Wärtsilä two stage turbocharged engines have operated in field for hundreds of thousands running hours. New technology, new learnings. Engine do not break down from poor performance, mechanical limits are exceeded before failure. Questionable performance will speed up the process.

The compact turbocharging system direct design towards need of sophisticated service concepts. E.g., turbocharger cleaning procedures, improved cartridge concept and standstill air cooler washing.

Service spaces need to be carefully considered. Narrow engine room without proper safety measures make service impossible. Empty space is not needed, space should be in the correct area.

Engine room design for two stage turbocharged engine needs careful examination for lifting point locations which become important with double component count. The crane must be able to reach also high-pressure turbocharger area located after the low-pressure turbocharger.

Years with two stage turbocharging have led us to extended service and exchange interval of main components presenting clear benefit on operational expenses. The engines are operating satisfactory when following the engine operation manual cleaning procedures and service intervals developed based on operating fleet.

6 Next challenge for environmental protection

The last chapter of this work will open a window on next engineering challenges targeting for even more reduction of pollutant emissions. As known to those working in internal combustion engines field, the most recent mainstream process is now defined as "decarbonization", with the aim to burn fuels without carbon as chemical component, these fuels have been so defined "future fuels".

6.1 Decarbonization

Following Paris Agreement on Climate Change (2015) for limitation of world environmental temperature increase up to +1,5°C, in 2018 IMO released following rule related to GHG Greenhouse gas emissions: "Total annual GHG emissions from international shipping should be reduced by at least 50% by 2050 compared to 2008."
Greenhouse effect is responsible for Earth temperature increase, in the way that the radiation energy from Sun heat the Earth's surface but the atmosphere will then prevent the heat from returning directly to space, resulting in a warmer planet. Heat is so absorbed by greenhouse gases such as e.g. carbon dioxide, originated from burning fossil fuels: coal, oil, and natural gas. Current human-caused increases greenhouse effect.
Maritime stakeholders have to reduce the total emissions of both and new marine installation, in order to comply with those new regulations and keep their fleet operating; indeed, all Regulators released some calculation index and parameters, so to have a measurable status of current level of emissions and to allow the definition of a technical improvement plan to reach the set target. Details of parameters are not in scope for such paper.
It is enough to mention how this new process is a real revolution affecting human being, and the number of technical opportunities and challenges will drive the engineering job of next decades.

6.2 Future fuels

Wärtsilä as an engine manufacturer focused their plans on the usage of so called "future fuels", low or totally without carbon dioxide in chemical composition.
This is a radical change, make to comply with the decarbonization targets.
Figure 12 provides a percentage forecast of the future split of fuel sources, data are from DNV Maritime Forecast 2050 model, elaborated in line with GHG targets. Wärtsilä engines will burn those future fuels [5]: Hydrogen, Ammonia (NH_3) and Methanol (CH_3OH). In next rows some resume of each one.

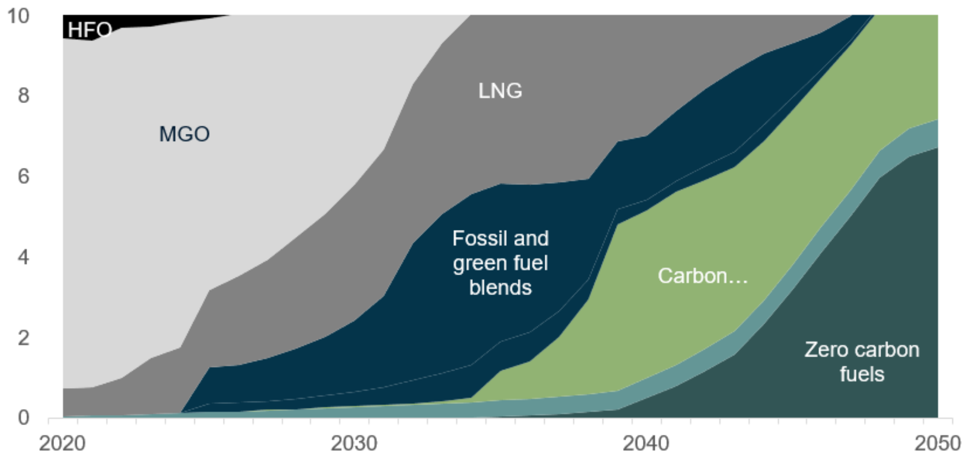

Figure 12: % split of fuel sources vs. time (source: Wärtsilä).

About 1st future fuel, is must be noted that Wärtsilä Dual-Fuel (DF) engines and Spark-Ignited (SG) gas engines can already operate with fuel blends of Hydrogen in LNG (liquified natural gas) comprising of up to 25%-vol hydrogen. First usage of hydrogen started in 2015 and now development is aiming to a pure hydrogen engine. Fuel distribution, storage and supply remain a challenge for hydrogen due to its low volumetric energy density. Current hydrogen supply is fossil based so in future the synthetic hydrogen will be the real gamechanger: it would have to be made in an environmentally sustainable way i.e., by electrolysis of water to hydrogen and oxygen by using renewable electricity.
Coming to the 2nd future fuel, she exploration of Ammonia (NH_3) as a fuel is progressing fast. It has several advantages over hydrogen, for example its greater energy density and it does not need to be stored under compression or at very low temperatures. But ammonia is toxic and highly corrosive, making it challenging to handle. Furthermore, also ammonia supply is currently fossil based so in future it would have to be made in an environmentally sustainable way with synthetic hydrogen and nitrogen as reactors. Wärtsilä is not starting from scratch in this area: there's several years' experience of designing cargo-handling systems capable of handling ammonia for use on LPG carriers; combustion tests with ammonia have been run in Wärtsilä fuel laboratory (2020), and currently full-scale Proof of Concept type technology development tests are running, with the aim to deliver first engine running on ammonia as pilot in marine market in 2024.
The 3rd so called future fuel is Methanol (CH_3OH): until now has not been widely used as a fuel, but it is a key component of decarbonization in the maritime industry. This easily and cheaply produced industrial alcohol as a better combustion and easier storage and handling than ammonia. Only a few marine engine builders have experience with methanol engines. A project to convert a Wärtsilä Z40 engine on the vessel Stena Germanica to burn methanol started operation in 2015. The engine now can run on methanol, and the success of the installation has inspired Wärtsilä to investigate further: in 2022 has been released the W32 Methanol engine and

MethanolPac® for off engine plant management; as for ammonia, the first pilot for marine customers is planned to be released in 2024.
Two stage turbocharging system is applied with future fuels because specific energy amount of those is lower than other fuels; so, it is easily explained how a boost effect is beneficial. Upboost will allow a better management of combustion phases with more waste gate operative margin, Miller effect reliability and a less thermal loaded 4-stroke engine.
As noticed in this short chapter, Wärtsilä is not focusing only on engine component and system design to run with future fuels, but also on handling and supply lines, covering maritime system as a whole package.

7 Conclusions

The journey presented in this paper represents one of the biggest development packages in the field of internal combustion engines. Within chapter 2 has been described how environmental protection is the key driver. Thanks to well-known scientific basis, such as chemistry, physics and thermodynamics, is possible to realize complex mechanical systems allowing optimum power outputs within technical and legislative boundaries, targeting reliability and costs control. Reader surely appreciated in chapter 3 how the solutions have been then extensively tested, and how the state-of-the-art engines have their roots in past 20 years of Wärtsilä history. Design, development and testing stages of chapters 4 and 5 are requesting high levels of optimizations and decision-based continuous improvement. Such described journey is never ending: some hints about future fuels and decarbonization have been provided in last chapter, and these open the door to the challenges of coming years. World is rapidly changing: if a product is manufactured on strong basis, as the ones listed in this paper, the upgraded versions of current products will be of high-quality level too, such as completely new ones, even if more complex.

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