

Computational Analysis of Internal and External EGR Strategies Combined with Miller Cycle Concept for a Two Stage Turbocharged Medium Speed Marine Diesel Engine

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ABSTRACT

In this work different internal and external EGR strategies, combined with extreme Miller cycles, were analyzed by means of a one dimensional CFD simulation code for a Wärtsilä 6 cylinder, 4 strokes, medium speed marine diesel engine, to evaluate their potential in order to reach the IMO Tier 3 NOx emissions target.

By means of extreme Miller cycles, with Early Intake Valve Closures (up to 100 crank angle degrees before BDC), a shorter compression stroke and lower charge temperatures inside the cylinder can be achieved and thanks to the cooler combustion process, the NOx specific emissions can be effectively reduced. EIVC strategies can also be combined with reductions of the scavenging period (valve overlap) to increase the amount of exhaust gases in the combustion chamber. However, the remarkably high boost pressure levels needed for such extreme Miller cycles, require mandatorily the use of two stage turbocharging systems.

Despite two stages turbocharging, combined with extreme Miller timings, may allow up to 50 % NOx reduction compared to a conventional, single stage turbocharger architecture, further NOx emissions reductions are necessary to meet the IMO Tier 3 NOx limit. Higher EGR percentages, which could be achieved by means of external circuits, were therefore also evaluated.

However, it should be pointed out that, although the external EGR technology is well established for automotive and heavy duty diesel engines, it is not yet state of the art for marine diesel engines, and its application to a highly boosted engine using extreme Miller timings is not straightforward.

Several different complex EGR routes were thus investigated, and for the preliminary assessment of their NOx emissions abatement potentialities, the use of numerical simulation allowed a detailed and extensive evaluation of the effects on engine performance, fuel consumption, NOx emissions and thermal and mechanical loads on engine components of the combination of different intake valve profiles, intake valve closure timings and scavenging periods with different external exhaust gas recirculation solutions.

Percentages of exhaust gases recirculated in the combustion chamber up to 20% were evaluated that combined with extreme Miller timings (up to 100 crank angle degrees before BDC) allowed up to 90% NOx reduction compared to a conventional, single stage turbocharger architecture, with only moderate BSFC increase.

INTRODUCTION

The increasing concern about the air pollution has resulted in the introduction of tighter exhaust emission controls also for marine engines equipping ocean ships. In particular the IMO (International Maritime Organization) Annex VI of MARPOL 73/78, which entered into force on May 2005,

establishing a first set of regulations for the marine engines exhaust emissions (IMO Tier 1 emission limits), has been undertaken a review with the intention to further reduce pollutant emissions from ships. IMO Tier 2 will enter into force from 1 January 2011, requiring further reductions of NOx emissions levels by about 20% from current IMO Tier 1 limits, while IMO Tier 3, entering into force from 1 January 2016, will impose NOx emissions reductions by about 80% from current IMO Tier 1 limits, although it will apply only in designated special areas, named Emission Control Areas, or ECAs, including the Baltic Sea, the North Sea, etc. as shown in [Figure 1](#) [1]. IMO NOx emission limits (Tier 1, Tier 2 and Tier 3 levels) are shown in [Figure 2](#).

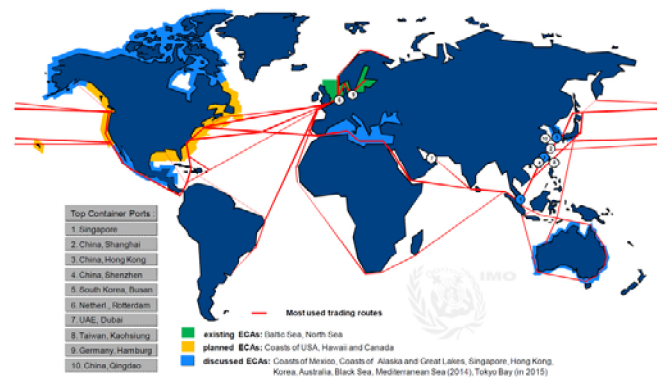


Figure 1. Emission control areas (ECA's) [1]

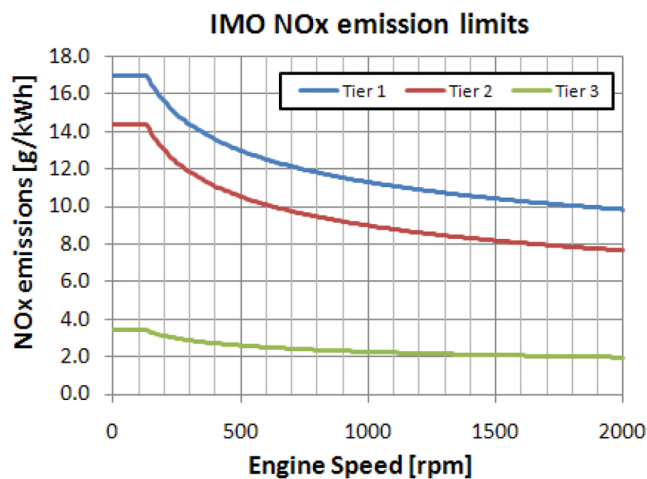


Figure 2. IMO Tier 1, Tier 2 and Tier 3 NOx emission limits.

Although different combustion and aftertreatment technologies could be combined in order to reach the IMO Tier 3 NOx emissions target, as shown in [Figure 3](#) [1], the aim of this work is the analysis of the potential of internal and external Exhaust Gas Recirculation strategies combined with Miller cycle concept [2,3] and dual stage turbocharging [4,5].

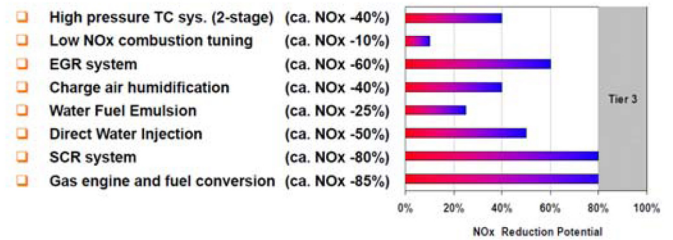


Figure 3. NOx reduction technologies potentials [1]

The Miller cycle [2] is an operating cycle for internal combustion engines which is essentially characterized by an effective compression stroke shorter than the expansion stroke, as shown in [Figure 4](#).

The cycle was originally conceived to increase the output power of turbocharged engines while maintaining within acceptable limits mechanical and thermal loadings on engine components, but has more recently gained considerable attention due to its capability to lower the peak in-cylinder temperatures, which makes it extremely attractive for its NOx reduction potential [5, 6, 7, 8].

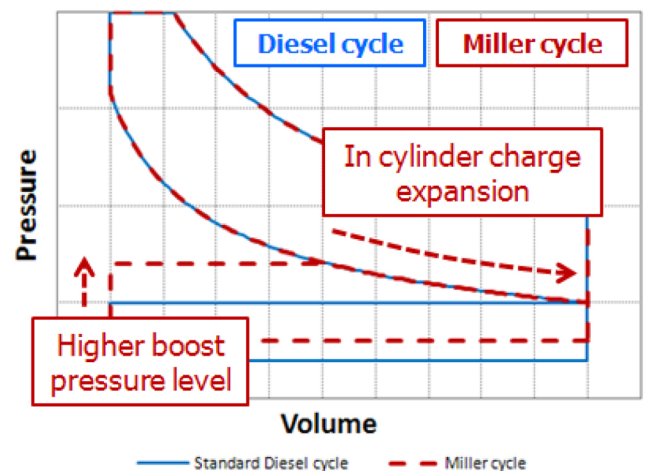


Figure 4. pV diagrams for the ideal Miller and ideal diesel cycle.

One possible way to reduce the compression ratio in the Miller cycle is the Early Intake Valve Closing (EIVC) strategy (see [Figure 5](#)). When the intake valve is closed before BDC, the air trapped into the cylinder will expand since the piston continues its outward movement. If the air temperature at engine intake can be assumed to be independent from the boost pressure, and if the boost level in the Miller cycle is increased so to reach the same in-cylinder pressure at the beginning of the compression stroke of a “standard” turbocharged engine, equal end-of-compression pressure levels will be attained in both engines, but with lower temperatures in the Miller cycle, as well as with an increased trapped mass of air (which could allow, at constant

air/fuel ratio, an increase of the injected fuel quantity and therefore of the engine power output).

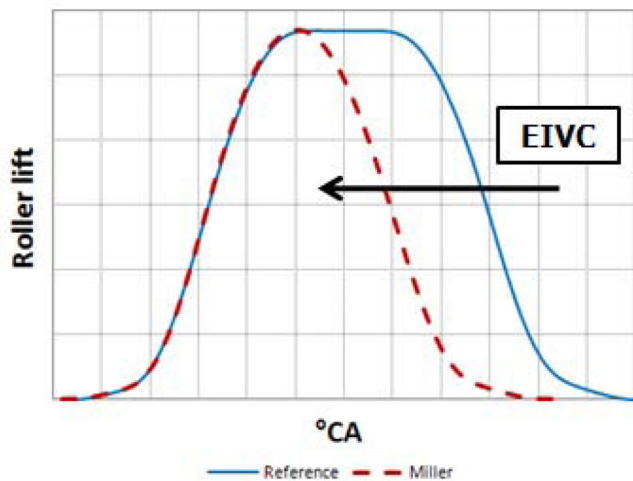


Figure 5. Intake valve lift profile with standard and Early Intake Valve Closing (EIVC) timings.

Positive effects of the lower temperatures inside the cylinder include, besides lower NO_x emissions, also lower exhaust and component temperatures and lower heat transfer from the charge to the combustion chamber walls (and thus lower thermal losses).

However, to achieve the high boost pressure levels needed for the Miller cycle, the use of two stage turbocharging systems is mandatory. To increase the system efficiency, interstage cooling of the intake air flow between low pressure compressor and high pressure compressor would also be necessary. A typical two stage turbocharging system layout with intercooler and aftercooler is shown in Figure 6.

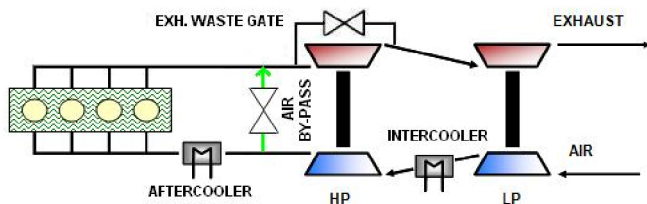


Figure 6. Two stage turbocharging system layout.

Nevertheless, although two stages turbocharging, combined with extreme Miller timings (up to 100 crank angle degrees before BDC) may allow up to 50 % NO_x reduction compared to a conventional, single stage turbocharger architecture [4,5], further NO_x emissions reductions are necessary to meet the IMO Tier 3 limits. In this case, one possible solution could be the combination of this combustion cooling strategy with the external Exhaust Gas Recirculation (EGR).

EGR involves mixing a portion of the exhaust gas, which can be previously cooled through a dedicated EGR cooler, into the intake air. This allows a further decrease of the combustion temperature as the combustion gases are diluted with inert gases with a lower local oxygen concentration. Although the external EGR technology is well established for automotive and heavy duty diesel engines, it is not yet state of the art for marine diesel engines, and its application to a highly boosted engine using extreme Miller timings is not straightforward. The recirculation of the exhaust gases has to be in this case achieved through the design of quite complex systems, since, differently from automotive engines, the pressure difference across the engine (from the intake to the exhaust) is positive, that means the exhaust manifold pressure is lower than the intake manifold pressure, thus not allowing the use of simple EGR short route systems with a direct connection between the exhaust and the intake receiver. Moreover, an additional difficulty is represented by the need to comply with ECA's low NO_x limits, while still maintaining the highest fuel economy elsewhere.

Several different complex EGR routes can be conceived, and for the preliminary assessment of the potentialities of each of them, the use of engine simulation tools plays a fundamental role, due to the huge amount of possible combinations between EGR layouts, boost levels, intake and exhaust valve lift profiles.

The aim of this work is therefore to set-up and to calibrate a fluid-dynamic engine model [9, 10, 11], coupled with a multi-zone combustion model for NO_x prediction [12,13], in order to evaluate the NO_x abatement potential of Miller cycle and dual stage turbocharging coupled with different external EGR systems.

A Wärtsilä 6 cylinder, 4 strokes, medium speed marine diesel engine was selected for the investigation, and, after a preliminary validation process, the engine model was used to evaluate the effects on NO_x emissions firstly of different combinations of dual stage turbochargers combined with extreme Miller cycles, and afterwards of the combinations with different external EGR architectures. In particular, four different external EGR layouts were analyzed.

The first one (which will be hereafter referred to as “intermediate connection”, see Figure 7) consists in a connection between the high pressure exhaust gas receiver and the low pressure air receiver, upstream of the high pressure compressor. Thanks to the relevant pressure gradient between the two volumes, the exhaust gases can be recirculated without the need of an additional EGR pump. This system allows avoiding power losses for driving EGR flow, but may not be feasible without the use of a diesel particulate filter or a scrubber on the EGR line when the engine is fuelled with Heavy Fuel Oil (HFO), in order to

remove particulates and sulphur compounds and avoid damages of the HP compressor and of the interstage cooler.

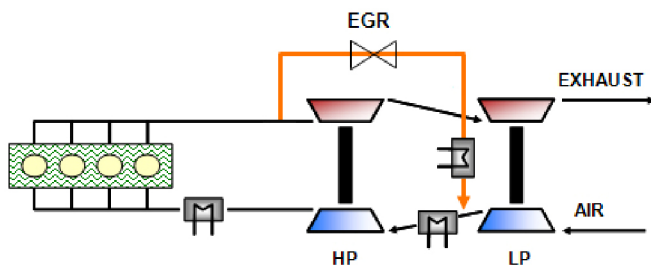


Figure 7. External EGR system #1: “Intermediate connection”

The second one (“EGR blower”, see Figure 8) features a short route connection between the exhaust and the intake manifold, with an electrically driven blower which is used to pump the exhaust gases, overcoming the pressure gradient. In this way, the drawbacks related to the flow of exhaust gases through the HP compressor and the interstage cooler are solved, although the equipment costs are increased significantly and, due to the electrical power required by blower, the impact on the fuel economy at higher EGR rates is significant.

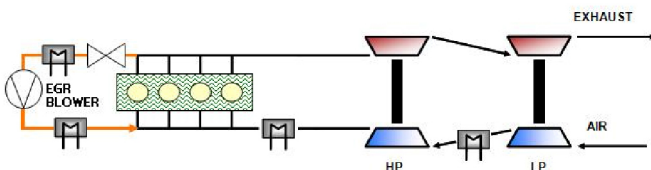


Figure 8. External EGR system #2: “EGR blower”.

The third one (“EGR turbocharger”, see Figure 9) consists again in a short route connection between the exhaust and the intake manifold, but instead of the electrically driven blower, an additional small turbocharger is used to pump the EGR flow. In this way, since no external power source is requested to drive the EGR flow, fuel economy could be improved in comparison with system #2, although the EGR turbocharger design may be complicated by the significant differences between the flows and pressure ratios of the turbine and of the compressor.

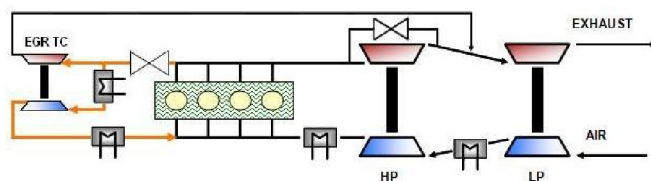


Figure 9. External EGR system #3: “EGR turbocharger”.

Finally, the fourth solution (“Back pressure driven EGR”, see Figure 10) uses an additional power turbine connected in series upstream of the high pressure turbine, as shown in Figure 10. The small size of this power turbine allows increasing the backpressure level above the boost pressure level, enabling the recirculation of exhaust gases from the exhaust to the intake receiver. Obviously the main drawback is the worsening of the pumping work, which becomes negative (i.e. transferred from piston to cylinder gases), although the fuel penalties could be mitigated by connecting the power turbine to an electrical generator in order to recover the turbine power.

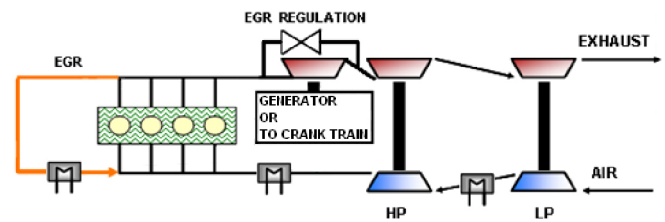


Figure 10. External EGR system #4: “Backpressure driven EGR”.

MODEL SET-UP AND VALIDATION

The main engine specifications are listed in Table 1.

Table 1. Main design features of the test engine.

Bore	200 mm
Stroke	280 mm
Compression Ratio	16
Speed	1000 rpm
Maximum Power	200 kW/cylinder
BMEP	27.3 bar

Computer simulations were carried out using GT-Suite, a one dimensional CFD code developed by Gamma Technologies for engine performance prediction (see [9, 10, 11] for more details), coupled with a multi-zone combustion model for NOx emissions prediction [12,13].

The experimental data for the engine model set up were provided from previous Wärtsilä investigation work [4]. The engine model was calibrated in two steady state operating points, showed in Table 2.