CHALMERS

Review on Recent Advances for Marine Turbocharger Technologies

For Two-stroke Diesel Engines

Bachelor’s thesis in the Marine Engineering Programme

Naomi Andersson
Erika Kisbenedek

Department of Mechanics and Maritime Sciences
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2018

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Department of Mechanics and Maritime Sciences
Chalmers University of Technology
SE-412 96 Gothenburg
Sweden
Telephone: + 46 (0)31-772 1000

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Department of Mechanics and Maritime Sciences
Chalmers University of Technology

Abstract

The study addresses the recent advances within the turbocharging technologies for two-stroke marine diesel engines and their advantages and disadvantages. The study also investigates which technologies will be of interest for future developments and most suitable for two-stroke engines. Emphasis is also put on the environmental impact of the shipping industry since it is responsible for the majority of the world trade and a large portion of the yearly global emissions. Two-stroke engines are dominant in the marine industry thanks to the power density and reliability. However, two-stroke engines are also quite insensitive to fuel quality and therefore low quality fuels are often used which have environmentally damaging emissions. Since the fuel economy is of importance to shipping companies, slow steaming is currently a popular method due to the lowered fuel consumption. The current turbochargers installed on two-stroke marine engines are not optimized for slow steaming and can lead to poor combustion. In the background, a motivation is presented and in-depth details describe two-stroke engine characteristics, differences between four-stroke and two-stroke engine turbocharging and the turbocharger working principle. A literature study was performed in order to achieve results capable of answering the questions of this thesis. The study is based on existing material in the chosen field.

Keywords: Marine Two-stroke, turbocharger, two-stage turbocharging, variable geometry turbocharging, hybrid turbocharging, turbocharger cut-out, Exhaust Gas Recirculation

Sammanfattning

Denna studie adresserar de senaste framgångarna inom turboladdningstekniker för tvåtakts marina diesel maskiner samt deras för- och nackdelar. Studien undersöker även vilka tekniker som är av intresse för framtida utveckling samt dess lämplighet för tvåtakts-maskiner. Betoning har även lagts på den marina industrins miljöpåverkan eftersom den ansvarar för majoriteten av världshandeln och en stor del av de årliga globala utsläppen. Tvåtakts-maskinerna är dominanta inom sjöfarten tack vare dess krafttäthet och pålitlighet. Tvåtakts-maskinerna är även relativt okänsliga för bränslekvalitet vilket bidrar till användning av lågkvalitativa bränslen, vars utsläpp är skadliga för miljön. Då bränsleekonomin har stor betydelse för rederier används slow steaming som en metod för att minska bränslekonsumtionen. Turboladdarna som är installerade på fartyg i dagsläget är inte optimerade för slow steaming, och kan orsaka en försämrad förbränning. I bakgrunden presenteras en motivation samt ingående detaljer som förklarar tvåtakts-maskiners egenskaper, skillnader mellan turboladdning för fyrtakts- och tvåtakts-maskiner och turboladdarens arbetsprincip. En litteraturstudie genomfördes för att uppnå resultat som kunde svara på frågorna i denna studie. Studien är baserad på material som existerar sedan tidigare inom detta område.

Nyckelord: Marin tvåtakts-maskin, turboaggregat, tvåstegsturbo, hybridturbo, avgasåterledning, variabel turbo

Acknowledgements

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Nomenclature

bmep	Brake mdean effective pressure
bsfc	Brake specific fuel consumption
CIMAC	International Council on Combustion Engines
CO_2	Carbon Dioxide
CO	Carbon Monoxide
EGR	Exhaust Gas Recirculation
HC	Hydrocarbon
HP	High Pressure
IMO	International Maritime Organization
LP	Low Pressure
NO_x	Nitrogen Oxide
PM	Particulate Matter
sfoc	Specific fuel oil consumption
SO_x	Sulphur Oxide
T/C	Turbocharger
VGT	Variable Geometry Turbocharger
VOC	Volatile Organic Compounds
WHR	Waste Heat Recovery

1. Introduction

The merchant shipping industry is highly competitive and relies a lot on speed efficiency, optimum fuel economy and meeting the environmental regulations (Anantharaman, Garaniya, Khan, & Lewarn, 2015). In the last few years, several regulations from the International Maritime Organization, IMO, have come into force regarding emissions from vessels all around the world. The regulations and conventions regarding prevention of air pollution from ships are contained in the International Convention for the Prevention of Pollution from Ships, also known as MARPOL 73/78 Annex VI. They are also often referred to as Tier I to III standards, where Tier III is the most recent (International Maritime Organization, 2018).

Most ships use a diesel engine as their propulsion method or prime mover. Depending on the size, type of cargo and purpose of the vessel, the diesel engine can run on the two- or four-stroke principles. For larger vessels the two-stroke diesel engine is a common choice (Anantharaman et al., 2015). The combustion process of the diesel engine results in emissions that contain pollutant gases, such as carbon dioxide (CO_2), carbon monoxide (CO), particulate matter (PM), nitrogen oxide (NO_x), hydrocarbons (HCs) and Sulphur dioxides (SO_2)(Andersson et al., 2016). These pollutants can have harmful effects on both humans and the environment. Carbon dioxide is considered a greenhouse gas which damages the Earth’s atmosphere. Both sulphur oxides and nitrogen oxides cause acid rain, though nitrogen oxide also causes ozone depletion. Soot and particulate matter are hazardous for the human ventilator system (Woud & Stapersma, 2002).

The efficiency and environmental imprint of the diesel engine depend partially on the air-fuel ratio in the combustion. The air-fuel ratio is significantly influenced by the turbocharger, which forces a large amount of compressed air into the cylinders, making it possible to increase the fuel flow, resulting in an increased power output and fuel efficiency.

There are several different types of turbochargers and turbocharging methods and there are currently no conclusive reviews regarding recent advances in marine turbocharger technologies, neither for the four-stroke or two-stroke marine engines. This thesis will investigate advances in sequential, parallel, variable geometry and hybrid turbocharging for two-stroke marine engines. Exhaust gas recirculation for two-stroke marine diesel engines will also be included since it involves turbocharging and has the purpose of reducing NO_x emissions.

1.1 Purpose

The purpose of this thesis is to review recent advances in turbocharger technologies for marine two-stroke engines. The thesis will investigate the advantages and disadvantages of the different turbocharger technology advances, to give an overview of which technologies that will be of interest for future development. Additionally, the thesis can be helpful for those wishing to get an overview in the field.

1.2 Questions

What recent advances have been made in the different turbocharging methods for marine two-stroke engines?

What are the advantages and disadvantages in those advances?

Which of these advances has most potential for future development regarding efficiency and emissions, and is most suitable for application on two-stroke diesel engines?

1.3 Delimitations

This thesis will focus on turbocharger advances for two-stroke marine diesel engines. To evaluate the most recent advances, material older than 10 years has not been included. The study is limited to a theoretical level, since the authors do not have access or time to follow up a field study.

2. Background and Theory

This chapter presents a motivation describing how this thesis is relevant to society. In addition, an overview on the two-stroke low speed engine is included, explaining how the two-stroke engine is dominant in the shipping industry and describes differences between the two-stroke and four-stroke diesel engine. The turbocharger's main components and working principle are introduced with differences in turbocharging for two-stroke and four-stroke engines.

Several articles used in this thesis were acquired from the thesis supervisor and are published on a technical database belonging to the International Council on Combustion Engines (CIMAC). CIMAC is a non-profit association consisting of members from 26 countries in Europe, America and Asia. The members have professions in relation to combustion engines, such as engine manufacturers, component suppliers, classification societies, universities, ship owners, research organisations and fuel and lubricant companies. Companies such as ABB, MAN Diesel & Turbo, Wärtsilä, Maersk, Scania and Alfa Laval have employees that are members of CIMAC (CIMAC, 2018).

An integrated research and development, R&D, programme called HERCULES, High Efficiency Engine R&D on Combustion with Ultra Low Emissions for Ships, was initiated in 2004 by MAN and Wärtsilä. The main focus of the project was to develop new technologies concerning engine efficiency, engine reliability and reduced gaseous and particulate emissions. The programme was divided into three phases called HERCULES-A, B and C and lasted for a duration of 10 years. The R&D programme had a research budget of approximately 80 million euros, and was partially financed by the European Union.

The first phase of the project, HERCULES-A, put emphasis on emission abatement and 42 partners were involved. By the end of the first phase, the objectives narrowed down to specific fuel consumption (sfoc), NO_x emission and other emission components, such as particulate matter, hydrocarbons and SO_x. The results from HERCULES-A lead to the possibility of narrowing down search areas and focus on developing techniques with more potential. One of the achieved objectives of HERCULES-B was multistage turbocharging, with 8 bar charging pressure on a test engine. Another achieved objective was the emission reduction method, using EGR on a test engine to achieve NO_x reduction of more than 50 % with regard to IMO Tier I. HERCULES-C, the last phase, integrated technologies from the previous phases. Multistage turbocharging and Emission Reduction from phase A combined with Intelligent turbocharging and Extreme EGR from phase B were integrated in phase C and renamed as Integrated Emission Control Technologies (N. Kyrtatos, Hellberg, & Poensgen, 2013). A concept study was performed, where a test engine was equipped with two-stage turbocharging and an EGR. The aim of the study was to fulfil the IMO Tier III regulation and to evaluate emission control systems. The development of an electrically driven EGR blower and advancing variable turbine geometry and compressor map width enhancement was also included. The study found that the amount of NO_x emitted from the test engine was reduced by over 80 % and therefore in compliance with IMO Tier III, by two-stage turbocharging in combination with an EGR (HERCULES-C, 2014).

2.1 Motivation

Shipping constitutes most of the world trade since approximately 90 % of all goods are transported by vessels. The need for shipping is constantly increasing on account of the expanding population and economy, combined with the cost effectiveness and low environmental imprint of shipping in comparison to other freight methods regarding carbon efficiency. Several studies on greenhouse gases have been investigating the emissions that come from the shipping industry. According to IMO's third greenhouse gases study, shipping is responsible for 972 million tonnes of CO_2 which amounts to 2.8 % of the global emissions (Andersson et al., 2016 p. 179). Among the 2.8 % of global emissions, circa 65 % of emissions from vessels are produced on container ships, tankers and bulk carriers as they represent 60 % of the world fleet (Mondejar et al., 2018). A major contributor to the exhaust emissions from ships is the use of fossil fuels, where the fuel quality can vary since the diesel engines are relatively insensitive to fuel quality. This allows low-quality high sulphur fuels to be burned, which evidently result in harmful emissions. The exhaust emissions that are most strictly regulated are CO_2, SO_x and NO_x, which can have transboundary impacts. During the economic crisis between 2007 and 2012, vessels reduced their average speed with the purpose of decreasing fuel consumptions which instead resulted in a 13 % reduction of total emissions (Andersson et al., 2016 p. 179).

Slow steaming has been utilised over recent years on many vessels since it is an effective way for the shipping companies to save money and it is seen as a characteristic of marine shipping (Sakamoto et al., 2016). While reducing the consumption of high-priced fuel is of importance for the shipping companies, optimized and improved turbocharger efficiency is a necessity. The development of turbochargers is required to address the most recently mentioned issue, mind the exhaust gas regulations and be customized for low load operations (Ono, 2013). Development of turbochargers is considered to substantially complement and improve the overall efficiency of the marine slow speed diesel engine. Superior design methods and software employment will lead to reduced emissions together with turbocharger improvement (Anantharaman et al., 2015).

2.2 The two-stroke low speed engine

The majority of the container ships and bulk carriers are powered by two-stroke diesel engines whilst tanker vessels have an equal amount of vessels powered by four- and two-stroke engines, which can be seen in Figure 1. The two-stroke diesel engine is dominant in the shipping industry due to different factors regarding size and power density, for instance. The engine's low speed allows the propeller to be directly coupled to the engine, eliminating the need for an expensive gearbox and thus eliminating the gearbox efficiency losses. Low speed engines have a relation to large propeller diameters, leading to higher propeller efficiencies. The ratio of propeller diameter to propeller pitch can be optimized, depending on the relationship between the propeller diameter, efficiency and speed (Anantharaman et al., 2015).

Figure 1

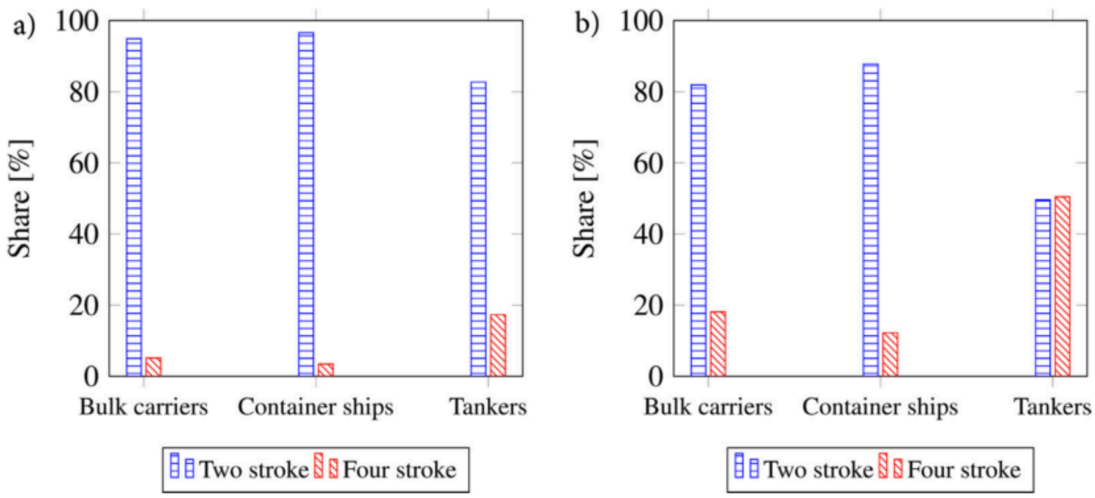

Figure 1. The engine power and number of bulk carriers, container ships and tankers equipped with four-stroke and two-stroke diesel engines. a) represents the main engine power. b) represents the number of units. (Mondejar et al., 2018) Reprinted with permission.

The most significant factors differentiating the two-stroke engines from four-stroke engines are speed, size and power density. The two-stroke engines are larger, with a crosshead connected between the piston rod and the connecting rod, due to the longer strokes and higher lateral forces. Two-stroke engines are therefore often referred to as crosshead engines, and four-stroke are often called trunk engines. A two-stroke engine can have shaft power between 1500 to 100,000 kW and speed of 50 to 250 RPM. A medium speed four-stroke engine's shaft power can be between 500 to 30,000 kW, and run at 400 to 1000 RPM. (Kuiken, 2008)

There are several differences between four-stroke and two-stroke turbocharging, for example the gas exchange and scavenging dynamics. The two principals have different requirements in turbochargers, making concepts that function well for a four-stroke engine insufficient for the two-stroke engine, one of the reasons is because the two-stroke principle does not include a gas exchange stroke. The gas exchange process includes scavenging, the replacement of exhaust air with fresh air, and is the segment where the exhaust gases after combustion are removed from the cylinder. Due to the two stroke engine's design, uniflow scavenging is seen as the only viable scavenging method (Ryser, Mathey, & Mutter, 2016). Uniflow scavenging is shown in Figure 2 and is a design in which the intake air and exhaust gases flow in the same direction, with inlet and outlet ports at opposite ends of the cylinder.

Figure 2

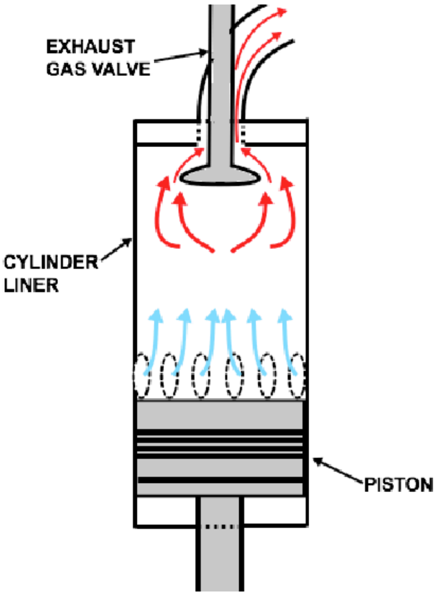

Figure 2. Example of uniflow scavenging, blue arrows depict fresh air and red arrows depict exhaust air. Author's own figure.

2.3 The turbocharger

The exhaust-gas turbocharger in marine applications consist mainly of an axial turbine and a radial compressor, this in order to increase the efficiency due to the large size of the marine turbochargers (Stone, 2012). The turbine and compressor are connected with a shaft, that is surrounded by a rotational assembly, with well lubricated bearings fitted to allow the shaft to rotate at high speeds (Sakamoto et al., 2016).

The working principle of the turbocharger is that the remaining exhaust gases after combustion are pushed out from the cylinder, by the air flowing upward in the cylinder through the scavenge ports. The exhaust gases enter the exhaust gas manifold and then pass through the turbine of the turbocharger. The exhaust gases drive and rotate the turbine, that is connected to the compressor, which simultaneously draws in and pressurizes air that passes through an air cooler and scavenge air receiver before entering the cylinders. The intention of pressurising the inlet air is to increase the density of the air, which allows a larger quantity of air in to the cylinder, which permits an increased amount of fuel in the combustion, thus resulting in a higher power output. (Woud & Stapersma, 2002)

During low-load operations and start-up of the engine, the amount of air that the turbocharger is able to supply for the combustion is insufficient. Electrically driven auxiliary blowers, that are internal parts of the engine, can either start operating before the engine is started to ensure safe starting operations, or start automatically when the engine load is under a certain percentage, and supply an increased amount of air. Auxiliary blowers are not needed on medium or high speed engines. (Wärtsilä, 2018)

The turbocharging systems have several characterizing parameters that may have an impact on the engine's performance, such as intercooling temperature, charge air pressure, turbine flow characteristics, waste gate rate, partition of overall pressure ratio on the compressors and turbocharging system efficiency. For turbocharger suppliers, it is important to supply turbochargers with appropriate compressor pressure ratios and high efficiency of the turbocharging system. (Ryser, Mathey, & Mutter, 2016)

2.4 Emission Regulations

In 2010, the main changes made after the revision of MARPOL Annex VI entered into force. The Emission Controlled Areas (ECAs) were introduced, where air pollutants such as SO_x, NO_x, Ozone Depleting Substances (ODS) and Volatile Organic Compounds (VOCs), are more strictly limited in certain sea areas (Internation Maritime Organization, 2018). The sea areas included in ECA are the Baltic Sea, the North Sea, coastal areas in the United States and Canada and some islands in the United States Caribbean Sea. Since 2015, vessels traveling inside ECAs must use fuel with a sulphur content of under 0.10 %. Outside the ECAs, the permitted sulphur content is 3.50 %, for the time being. After assessing the fuel availability, it was decided that the permitted sulphur content outside ECA will be lowered to 0.50 % in year 2020. Besides using low-sulphur fuels, exhaust gas cleaning systems and scrubbers are examples of approved alternatives to meet the SO_x requirements (International Maritime Organization, 2014).

The NO_x control requirements in MARPOL Annex VI are divided into different levels called Tiers. The NO_x regulations apply to vessels with an installed marine diesel engine power output of over 130kW, excusing vessels that only are used for emergency purposes. Table 1 shows the three Tier regulations from IMO. The factors that determine the application of the different tiers are the date of construction and the engine's rated speed, which can determine the amount of NO_x in g/kWh. For vessels traveling within ECA, the Tier III regulations apply and outside ECA the Tier II regulations apply (International Maritime Organization, 2018).

Table 1				
Tier	Construction Date	rpm<130	130<rpm>1999	rpm>2000
Tier I	01/01/2000	17.0	$45 \cdot rpm^{(-0.2)}$	9.8
Tier II	01/01/2011	14.4	$44 \cdot rpm^{(-0.2)}$	7.7
Tier III	01/01/2016	3.4	$9 \cdot rpm^{(-0.2)}$	2.0

Table 1. Tier Regulations chart including construction date, rpm and NO_x emissions in g/kWh. (International Maritime Organization, 2018)

3. Method

To answer the questions of this review thesis, a literature study has been performed as the main method. The method was chosen because the study is based on other already existing material in the chosen field. The authors have used the methodology book "Doing Qualitative Research" (Silverman, 2005) during the process as a guide on how to write a literature review. Materials used in the thesis are conference proceedings, journal articles and relevant literature acquired from different search motors, databases and the thesis supervisor. Information found on turbocharging manufacturer's websites has been included. The authenticity and credibility of the sources of information has been determined by the relevance to the subject. The authors focus on mentioned developments, technologies, advantages and disadvantages when reading and summarizing the material.

Library:
Chalmers Library

Databases:
CIMAC, Chalmers Library, Summon, Science Direct, Google Scholar, Elsevier, Google.

Keywords:
Turbocharger, marine two-stroke, sequential turbocharger, two-stage turbocharger, parallel turbocharger, hybrid turbocharger, exhaust gas recirculation, variable geometry turbocharger, IMO MARPOL Annex VI, cut-out,

Selection:
When selecting the used articles, the authors began the search quite widely on the subject, in order to get an overview of how many papers could be found. The articles that were most relevant, depending on the title, were chosen, added to an excel file, briefly read and then categorized after technology type. In the second stage of the selection, the authors performed another search, which was more directed to the different technologies found in the first stage.

4. Results

The chapter presents the results of the literature study. The results are divided into sections, each with a brief description of the specified turbocharger technology, followed by a summary of the articles that were used. The results are concluded with a brief analysis of advantages and disadvantages of the advances in the technology, according to what was found in the articles.

4.1 Two-stage turbocharging

Two-stage turbocharging consists of two single-stage turbochargers of different sizes. The turbochargers support either low- or high-pressure operations, and are regulated by a by-pass valve (Nguyen-Schäfer, 2012). The low-pressure (LP) turbocharger is smaller sized and used under low speeds and low pressure ratios. The high-pressure (HP) turbocharger is larger, and operates with a constant compressor volume flow during a smaller range of higher pressure ratios. The two turbochargers are connected in series, as shown in Figure 3, and are able to run at different speeds. Intercoolers are placed between the compressors in order to increase the air density and it also increases the efficiency of the turbocharging system (Woud & Stapersma, 2002).

Figure 3

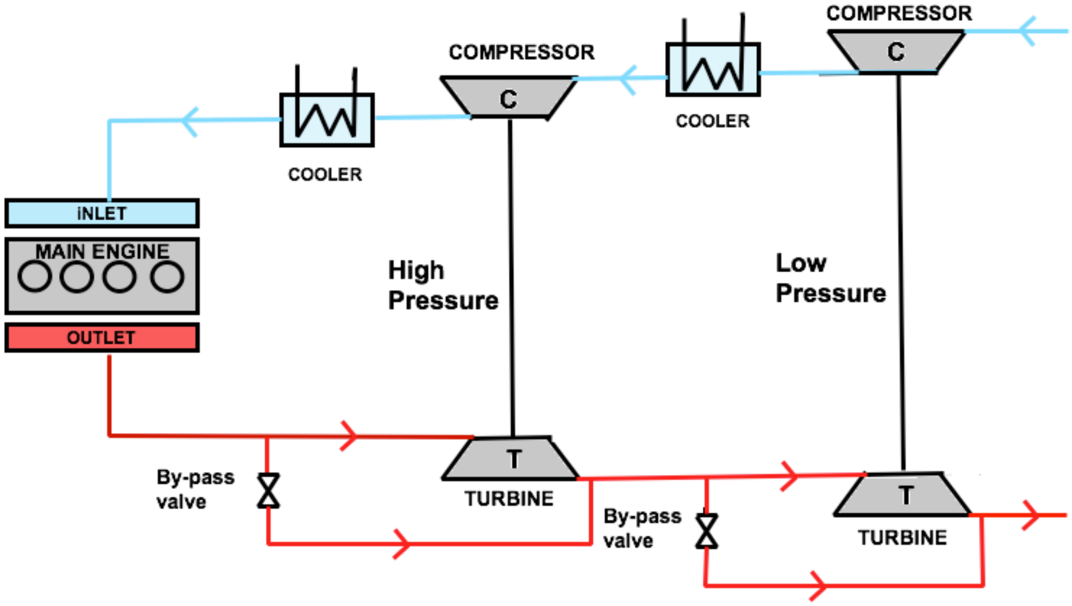

Figure 3. Illustrative figure of a simple two-stage turbocharging configuration. Author's own figure.

There are several manufacturers on the market that provide different two-stage solutions. The technique has been a big success in four-stroke engine applications, but the two-stroke engine application is still under evaluation. The manufacturers are currently working on providing suitable applications for two-stroke engines. ABB Turbocharging presented solutions and ideas on how to proceed with the technique, to suit the popular two-stroke engine, at the CIMAC congress in both years 2013 and 2016. Schuermann et al., (2013), from ABB Turbo systems presented different application cases, for two-stage turbocharging on two-stroke marine engines, at the CIMAC congress held in Shanghai. The cases were based on experience from preceding tests and extensive simulation exercises. The authors explained that the benefits of improving turbocharger efficiency applied on two-stroke engines are limited. To exploit the benefits of improved turbocharger efficiency by applying two-stage technology, two potential engine developments can be considered; applying a Waste Heat Recovery (WHR) system and increasing the engine brake mean effective pressure (bmep).

The WHR system, or turbo compound, is in this case power turbines fitted at several points in the two-stage turbocharging system. The power turbines generate electricity from the excess exhaust gases in the system. Higher efficiency is gained from a two-stage turbocharging system, compared to a one-stage system, and a higher power output also, which can provide the power turbine with higher mass flow. The results show that the two-stage setup with WHR has potential of large fuel savings, by reducing the bsfc up to 5% compared to one-stage turbocharging, but the high first cost of installing the WHR is a disadvantage.

The advantage of increasing the engine's bmep from 21 up to 30 bar, by reducing the cylinder bore diameter or the number of cylinders, together with two-stage turbocharging is the possibility for extreme downsizing of the engine.

Ryser et al., 2016 from ABB Turbocharging presented a paper at the CIMAC congress in Helsinki, which investigated additional complements to ABBs Power2 2-stage turbocharging technique. The paper discussed two-stroke engine characteristics, turbocharging requirements, parameters for the low- and high-pressure stages and ABB's Power2 systems. The authors investigated the application of variable intake port height and timing. Two variable intake port methods were discussed; the first method is leaving the air intake port timing symmetric, with variation of port height at different loads. The second method is having asymmetric intake port timing. The investigations were done by simulation of a low speed engine with 50 cm bore class. The result showed that high port height with medium load and low port height together with high load, gave a positive effect on fuel consumption when adapting the two-stage turbocharger system.

The result of these investigations and tests show clearly that a solution for effective two-stage T/C, suiting a low speed two stroke engine, involves more than just having a state of the art T/C. The interaction between the turbocharger and the engine is of great importance. Manufacturers must consider making possible changes to both the T/C and engine, in order to achieve an optimized solution.

4.2 Turbocharger cut-out

The parallel turbocharger principle is the most common arrangement on existing marine two stroke engines. It consists of two identical turbochargers connected in parallel to the exhaust gas receiver. The parallel turbochargers can either be of the same size or parallel two-stage. If the turbochargers are of the same size, they equally share the load, and are commonly called twin turbochargers. Figure 4 is an example of a simple parallel turbocharging configuration.

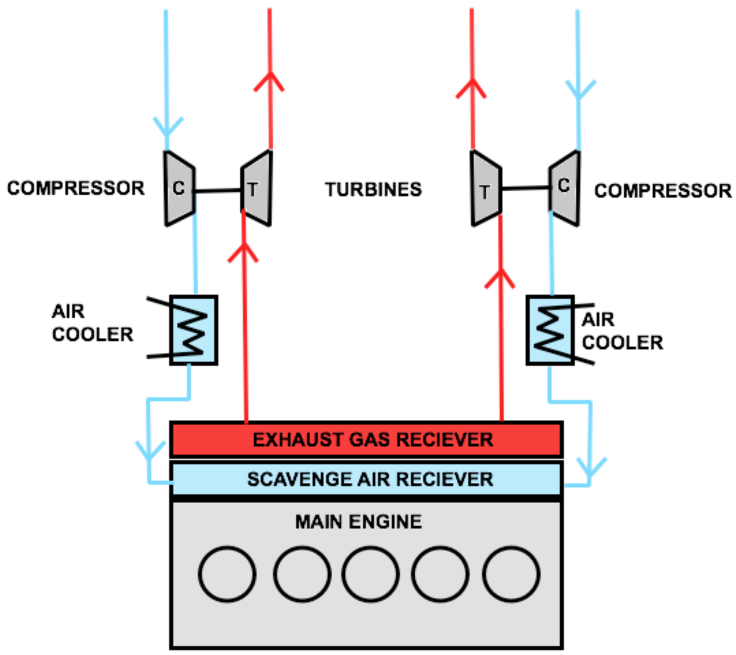

Figure 4. An example of a simple parallel turbocharging configuration. Author's own figure.

Turbocharger cut-out is used on engines with two or more parallel installed turbochargers to reduce the fuel consumption at low-load operation. When the engine operates at low loads, the turbocharger speed is decreased. Thus, the temperature of the air supplied to the engine is too low, which leads to a less than optimal combustion process. To increase the speed of the turbocharger, cut-out methods where one or more turbochargers are cut-out from operation, can be used (Wehner, Schmidt, & Pamungkas, 2017).

MAN Diesel & Turbo, (2018) offer two turbocharger cut-out solutions for two-stroke low speed engines. The cut-out can be applied by installing blinding plates on the air outlet, and also on the exhaust gas in- and outlet of the turbocharger. Installing gate valves on the air outlet and exhaust gas inlet of the turbocharger is also a mentioned approach. ABB Turbocharging also offers two types of cut-out methods for their turbochargers, the "fixed cut-out" and the "flexible cut-out" (Baechi, 2012). In the first method the gas, air, and oil lines are disconnected, and the bearing and rotating parts are removed. The second mentioned method involves installing a charger and flexible valves in the gas and air lines.

Guan, Theotokatos, and Chen, (2015) investigated the effects on the engine performance at low load by applying turbocharger cut-out on a two-stroke marine engine. A zero-dimensional model of the MAN B&W 7K98MC two-stroke engine was used, in a simulated environment built in Simulink and MATLAB. The model used an electrically driven blower and three turbochargers connected in parallel to supply air to the engine. To increase the reliability of the engine during low load operations, electrical blowers are used. The electrical blowers increase the amount of air to the engine, the turbocharger speed and the scavenging pressure. The application of turbocharger cut-out reduces the need for blower activation and decreases the consumption of electrical energy. The result of the study showed that the following cut-out methods were preferred when aspiring to achieve a positive effect on fuel costs and environment.

- one cut-out turbocharger without activated blower at 50 % to 25 % load
- two cut-out turbochargers without activated blower at 20 % to 15 % load
- two cut-out turbochargers with activated blower at 10 %

According to the authors, the fuel consumption and CO_2 emissions can be reduced with approximately 2 % for a panamax containership, during slow steaming in combination with the mentioned turbocharger cut-out arrangement, compared to regular operation.

4.3 Variable geometry turbocharging

Two stroke marine engines often run at low loads, and the variable geometry turbocharger technology is used to increase the boost pressure at low speeds, by mechanically changing the geometry of the turbine housing. Controlling the boost-pressure enables the possibility of using a wider range of the T/C operation, which can contribute to achieving a better fuel economy and reduction of the engine emissions. There are different techniques available on the market offered by several manufacturers, who all aspire to implement movable components to the turbocharger. Implementation of movable components can lead to achieving the mentioned benefits. There are systems available that can be applied on both the turbine and compressor. A common solution is movable vanes, that can be opened and closed depending on the engine load to allow a suitable air flow to the engine (Feneley, Pesiridis, & Andwari, 2017). Figure 5 is of an automobile variable geometry turbine where the vanes are shown in open and closed position. Figure 6 displays an VGT from a different angle where the vanes are more exposed, the closed position is shown firstly and then the opened position.

Figure 5

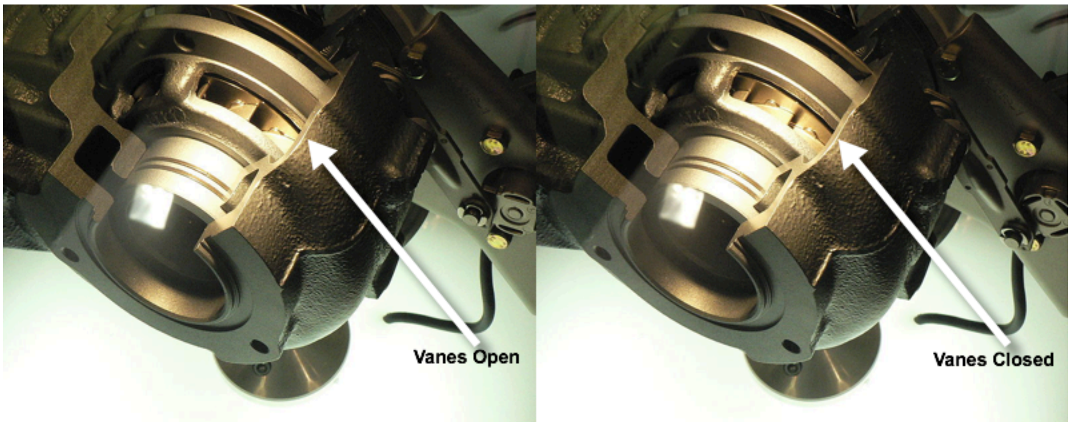

Figure 5. Sectional models through a turbocharger housing with a view of the movable vanes. (Ton1, 2006) CC BY-SA 3.0

Figure 6

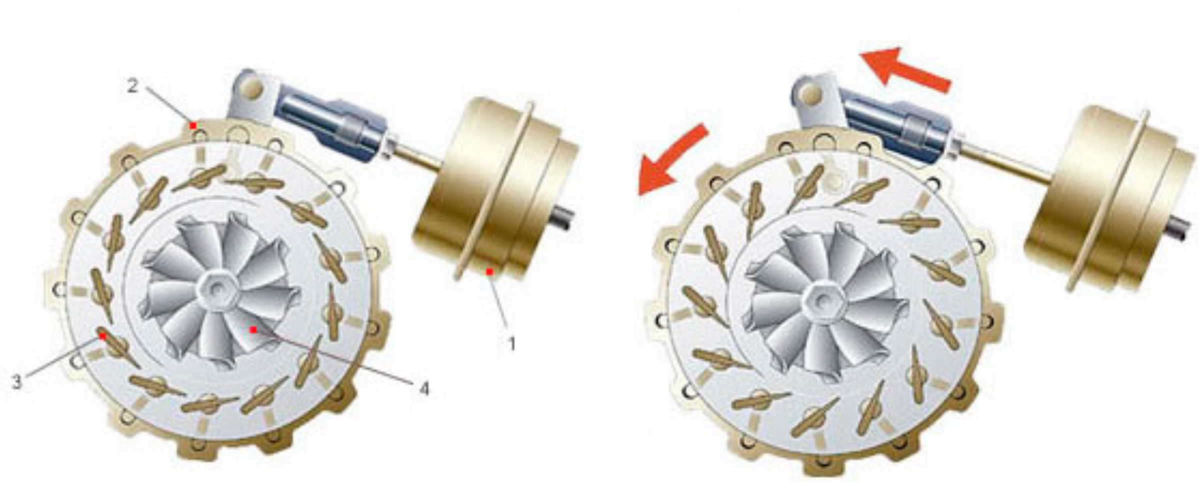

Figure 6. Variable geometry turbines vanes shown firstly in closed and secondly in opened position. (Feneley et al., 2017) Reprinted with permission.

Mitsubishi Heavy Industries - Machinery & Equipment CO., LTD. (2017) (MHI-MME) has developed a variable geometry turbocharger called variable turbine inlet (VTI) turbocharger. The T/C has a variable turbine nozzle. The nozzle can be switched between two stages to enable reduction of the nozzle area, resulting in an increased scavenging air pressure at low load engine conditions. Sakamoto et al., (2016) from MHI-MME presented the latest technology for Mitsubishi turbochargers at the CIMAC congress held in Helsinki. MHI-MME has focused on improving turbocharger efficiency for low load operations, by further developing the VTI turbocharger. The new compressor developments include a reduced number of diffuser vanes and optimized vane morphology, to increase the airflow capacity for the compressor. They compared the result of the new technology to their previous models, and found that the airflow capacity had increased by approximately 8 %. The reduced number of vanes give more space for creating the vane profile and require less steps during manufacturing of the compressor. The turbine development resulted in an increased number of blades that were made lighter to increase the turbine efficiency.

4.4 Hybrid turbocharging

The purpose of hybrid turbocharging is supplying the turbocharger shaft with additional torque during low loads, when the exhaust gas energy required for driving the compressor is insufficient. A high speed electric generator is connected to the turbocharger shaft, located on the compressor side of the shaft. At high loads it is used to generate electrical power and can replace the auxiliary blower at low loads by acting as a motor. (Ono, 2013).

In 2008, Mitsubishi Heavy Industries – Machinery & Equipment CO., LTD. developed a hybrid turbocharger called MET83MAG together with other companies, with the purpose of achieving fuel savings and meeting the environmental regulations. The turbocharger is integrated with a high speed generator, fitted inside the body of the turbocharger, directly connected to the rotor shaft of the T/C. The power supply system includes a permanent magnetic generator that generates a 3-phase alternating current, between 0-400 volts and 0-167 Hz, depending on the turbocharger speed. To make the electricity useful for ship application, where the normal power supply is often AC 450 V, 60 Hz, the system also consists of a converter that reforms the generated AC to DC, with constant voltage, and is assisted by an insulated gate bipolar transistor that is suitable for high frequency. The same transistor is also used for the final stage of the system, an inverter, to get a stable AC 450 V, 60 Hz stand-alone power supply. When developing this stand-alone power supply system some issues required investigation and were solved. Due to the fact that the system doesn't have a reference waveform when connecting it to the common ship supply, it was necessary to develop an autonomous control of frequency and voltage. It was also necessary to develop the supply of reactive power and sustained short-circuit current. Another problem during the development of the generator was creating a suitable cooling structure.

Figure 7.

Figure 7. Shin Koho, Japan (NYK Line, 2011). Reprinted with permission, courtesy of NYK Line.

The final product was tested with verification of the generator characteristics and turbocharger performance, including load, governor and temperature characteristics through bench tests. The bench tests were followed by an engine-matching test where the most suitable engine for the hybrid turbocharger was decided. Finally, in 2011, the system was installed on an actual bulk carrying vessel, Shin Koho, shown in Figure 7, and after successful sea trials the vessel is still in operation, using the MET83MAG hybrid turbocharger application. An advantage of the mentioned application is that it can easily be installed on engines currently in use, due to the few modifications required for the installation (Ono, Shiraishi, & Yamashita, 2012).

4.5 Exhaust gas recirculation

Exhaust gas recirculation, EGR, is a method which reduces NOx. The formation of NOx occurs during high combustion temperatures and pressures. A portion of the exhaust gases is redirected back into the scavenge air receiver and mixed together with fresh air, in order to increase the heat capacity of the air and reduce the oxygen concentration in the cylinders. The method reduces the peak temperatures during combustion, therefore restricting the formation of NOx. The method requires a cleaning device, since the exhaust gases that are redirected may be harmful to the engine's components. Another important part of the EGR system is the blower. The blower is used to overcome the scavenging differential pressure and is one of the challenges of this technology. (Kyrtatos et al., 2016). The EGR technology has been successfully used in the automobile industry and for medium and high speed marine engines (Wang, Zhou, Feng, & Zhu, 2017). Recently, manufacturers have been focusing on implementing the technology for larger diesel engines, including large two-stroke marine engines.

MAN Diesel & Turbo have focused on the EGR technology, especially for large two-stroke marine engines. At the CIMAC congress in 2016, they presented recent development on their EGR technology with emphasis on the blower. MAN Diesel & Turbo together with PBS Turbo developed their own Electrical Turbo Blower (ETB) to improve the EGR process. When designing the blower, requirements for a functional EGR solution were established, and various compressor and system drive concepts were investigated and carefully considered. The radial compressor design was chosen since it fulfils the investigated requirements. The radial compressor has a wide compressor map, high efficiency at low pressure ratios and high-pressure pulsation stability. To withstand the sulphuric acids in the exhaust gases, the compressor wheel was made entirely of stainless-steel. For the system drive, a tailored high-speed electrical motor was selected to suit the requirements. The high speed e-motor is capable of continuously adjusting the rotational speed. and can achieve high efficiency since it is directly coupled to the compressor. A high speed motor without a gearbox is a more compact design that is able to transport the same amount of exhaust gases.

After the design process, the final prototype was established and verified through simulations, engine tests and field experiences. The ETB prototype was tested for two-stroke application at

MAN Diesel & Turbo's test centre in Copenhagen. The results were satisfactory, and the measurements met the Tier-III requirements. The ETB also proved to be stable when realistic pressure disturbances were tested. After the successful testing two ETBs were installed in parallel on the EGR engine 6S60ME-C8.2, situated on a real ship, which now is in service and under observation (Garshasebi, Schmuttermair, Kern, Stork, & Stefanak, 2016).

Wang et al., (2017) investigated the effects on engine performance and emissions, when implementing an EGR system combined with cylinder bypass (CB) and exhaust gas bypass (EGB), on a simulated two-stroke low speed engine. NO_x emissions, fuel consumption, engine power and emissions were analysed. The simulation model was constructed by the authors in GT-SUITE software. The simulated engine model was equipped with an EGR system using two loops, one EGR loop and one main loop and can be seen in Figure 8. On the main loop a cylinder bypass and an exhaust gas bypass were fitted, and the loop provides scavenging air receiver with fresh air through the turbocharger compressor and the cooler. The EGR loop lead the recirculated exhaust gases to the scavenging air receiver through a pre-scrubber, cooler, scrubber and Water Mist Collector (WMC). A blower was used to force the recirculated exhaust gases to the scavenging air receiver, due to the issue that the exhaust gas pressure is less than that of the scavenge air.

Figure 8

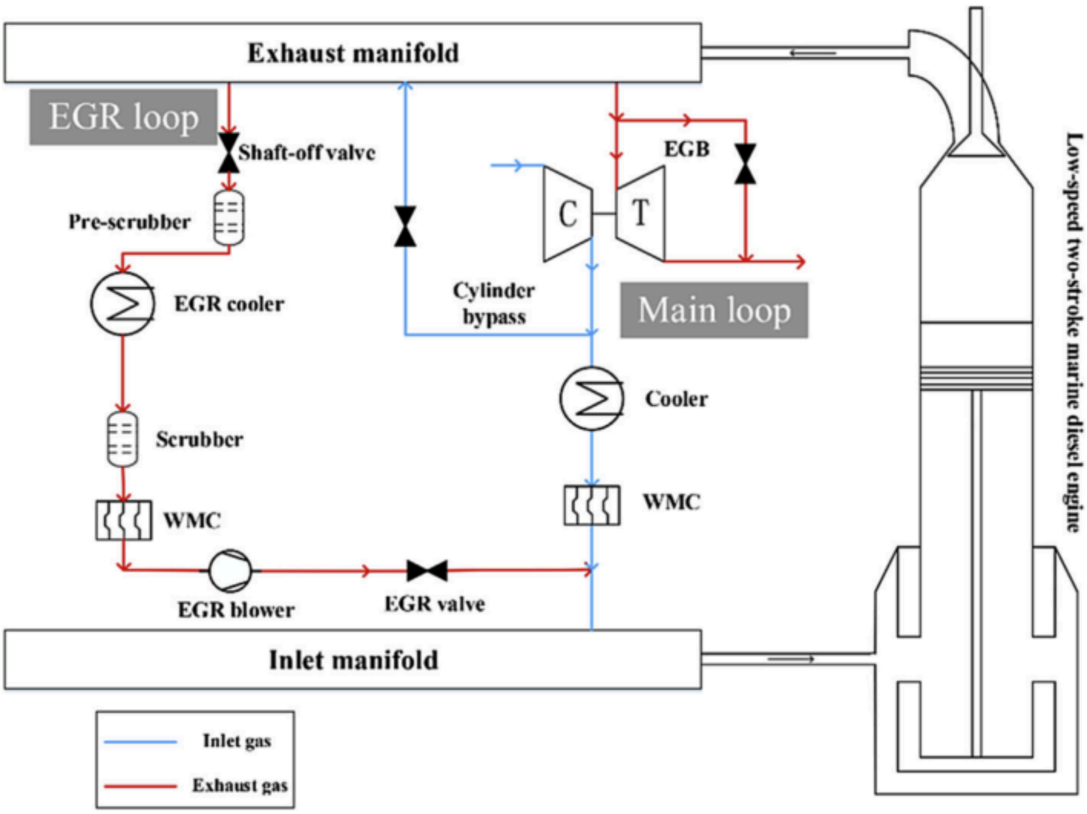

Figure 8. The simulated engine model's EGR, CB and EGB setup. (Wang et al., 2017) Reprinted with permission.

To control the EGR rate, the blower and EGR valve needed to be adjusted during the simulation. Three different modes were set and tested:

Non - EGR mode

- Set to meet the IMO Tier II regulation when ship is sailing in non-ECA
- Exhaust gas is not recirculated into the engine and CB was closed. Exhaust Gas Blower (EGB) valve partly open

Low – EGR mode

- Standard mode in non-ECA
- Main loop in operation with partly opened CB valve

ECA-EGR mode

- Set to meet the IMO Tier III regulation when ship is sailing in ECA
- The main loop was in operation and CB valve was open partly or fully in different loads to increase the scavenge air pressure and thereby to reduce the sfoc

All three modes were tested at four different operating loads: 25 %, 50 %, 75 %, and 100 % load.

The result of the simulated experiments showed that the NOx emissions were reduced in all three modes and that they met the Tier requirements at high loads. In ECA-EGR mode the NOx emissions were 3.15 g/kWh at 100 % load, which is within the Tier III limit. Both the Non-EGR mode and the Low- EGR mode reached the Tier II requirement with 12,9g/kWh receptively 10,3g/kWh in NOx emissions at 60 % load. Even though the NOx emissions decreased, the CO emissions and sfoc increased, which is the negative effect of the EGR system due to the lower temperatures that leads to a poor combustion. It shows that it is possible to reduce NOx emissions by having an EGR system together with CB and EGB on a two-stroke engine, but the challenges are the higher sfoc and CO emissions and the fact that the engine need to operate at high loads to get below the Tier limits.

4.6 Summarization

ABB's Power2 two-stage turbocharging system can be optimized by combining the T/C system with either an WHR or by increasing the engine's bmep.

- Combining the T/C system with WHR can potentially reduce the bsfc, improving the fuel economy.
- Installing a WHR system comes with a high first cost, which can be seen as a disadvantage.

Another additional complement to the ABB Power2 T/C system is implementing variable intake port timing and height.

- The result in the study showed positive effects on the fuel consumption when having high port height, during medium loads, and low port height during high loads.

The turbocharger cut-out simulation study, performed by authors that were not employed by manufacturers, showed

- Theoretically increased engine reliability
- Reduced need of blower activation, therefore reducing electric energy consumption
- Reduced fuel consumption
- Reduced CO_2 emissions

For Variable Geometry Turbocharging, developments of Mitsubishi's VTI showed the following

- Reduced number of diffuser vanes, requires less steps under manufacturing
- Increased air flow capacity for the compressor
- Increased turbine efficiency

The Mitsubishi Hybrid Turbocharger was described with several positive factors

- Generator function of the electrical motor can replace the auxiliary blower
- Generator can also be a source of electrical power supply
- Does not require any major modifications

MAN Diesel & Turbo's developed ETB included factors such as

- The compressor wheel is made of stainless steel and resists sulphuric acids
- The high speed electrical motor can achieve high efficiency
- Compact design
- Measurements show that the Tier III requirements were fulfilled
- Stable during pressure disturbances

A simulation study on the use of EGR combined with CB and EGB included the following factors

- Reduced NO_x emissions and fulfilled Tier requirements at high loads
- Higher sfoc
- Higher CO emissions
- Low load operations do not fulfil Tier requirements

5. Discussion

The results show that different turbocharging technologies for marine two-stroke diesel engines, is a quite narrow subject. The different types of technologies are, after all, products that the turbocharger manufacturing companies aim to sell. It is clear through all the articles and papers reviewed, that fuel efficiency and emission regulations are the main reasons behind the developments. The marine turbocharging industry is to some extent quite niche and it is unlikely to research the topic without any form of connection to it. Thus proving that majority of the found articles and papers were written by authors who were employed by the turbocharging companies, making them to some extent biased, and included few concretely stated disadvantages of the turbocharging products advancements. The authors of this thesis can imagine that it is seen as unnecessary, from a sales point of view, to present disadvantages in product advances. Therefore, it is difficult to properly answer the question regarding disadvantages in advances unless the advances have been investigated by an independent source. The articles that were written by independent sources were limited. Some reviews were found, where technologies were tested in simulations.

According to Ryser, Mathey and Mutter (2016) two-stage turbocharging for two-stroke diesel engines is still under development, but was put on hold for a while, since the thermal efficiency of two-stage turbocharging was weak in comparison to other turbocharging solutions. Even though other manufacturers also have solutions for two-stage turbocharging, no extensive information was found on the techniques used, therefore, articles only from ABB Turbocharging were included in the study. From the ABB Turbocharging articles, it is clear that the company is evaluating complementary alternatives to utilise the full potential of the two-stage turbocharging system for two-stroke engines. The present complementary alternatives are addition of WHR, increasing the engines bmep and implementing variable intake port height and timing.

When researching turbocharger cut-out methods, no further advances were found than the already existing options. Cut-out methods merely exist in the purpose of aiding the turbocharger’s functionality during low load operations. Cut-out methods have an indirect effect on the exhaust emissions by improving the combustion at low loads. Since the cut-out methods only involve cutting off turbochargers from operations, the advancement opportunities are limited. It is of the authors opinions that cut-out methods are used as a quick fix or supplement to other technologies during slow steaming, and is not a permanent solution for those wishing to improve their fuel economy whilst simultaneously actively taking action against exhaust emissions.

Within the VGT technology, Mitsubishi Heavy Industries - Machinery & Equipment CO., LTD. (2017) has further investigated new developments on their VTI turbocharger. The company’s aim is to create a suitable solution for slow steaming and continuously develop their products. According to the results, the air flow capacity of the VTI turbocharger is increased. The company has been able to reduce the expenses and increase the efficiency of the turbocharger, by decreasing the weight and mechanical parts. Disadvantages of the VTI turbocharger are unfortunately not presented. Regarding two-stroke implementation, the VTI turbocharger is definitely applicable since it is customised for slow steaming.

The hybrid turbocharger is a product from Mitsubishi Heavy Industries – Machinery & Equipment CO., LTD. and is currently installed on the vessel Shin Koho. In the presentation paper it was described as highly efficient, and easily installed. The generator can either generate electricity or be used as a motor to accelerate the turbocharger, and is also capable of replacing the blower during low loads. The paper did not present any disadvantages and therefore it is quite difficult to analyse, though it is possible to imagine that an extra motor and the necessary electrical components may cost a significant amount. The fact that Mitsubishi is currently the only supplier of hybrid turbochargers for marine two-stroke engines is interesting and the authors of this thesis are questioning why other turbine manufacturers have not also invested in hybrid turbocharging.

MAN Diesel & Turbo implement EGR methods with the purpose of reducing NO_x emissions. Recently the focus has been on applying EGR technology on two-stroke marine engines. The latest advance in the field is the development of their own ETB, which is used to improve the EGR process. The ETB proved to be successful after intensive testing and is currently in use and under observation on a real ship, to further investigate its suitability for two-stroke application. The displayed advantages of the ETB are Tier III fulfilment and the ability to handle pressure disturbances. No disadvantages were discussed in MAN Diesel & Turbo's own presentation. Although, disadvantages of an EGR system were discussed in a study performed by Wang, Zhou, Feng and Zhu. According to their study, only the NO_x emissions were decreased whilst the sfoc and CO emissions were increased. The study investigated if EGR was compatible with CB and EGB in a simulation. The results of the study showed that the NO_x emissions were reduced and Tier III limits were fulfilled, but only under high loads. The combination of slow steaming whilst using an EGR system to reduce NO_x emission levels seems to be insufficient. The thesis authors can imagine that this factor contributes to the fact that EGR is not as suitable for two-stroke engines as it is for medium or high speed engines in both the marine and automotive industry, since it is most efficient during high loads.

Attempting to decide which advance had most potential, for future development regarding efficiency and emissions, and was most suitable for two-stroke marine engine application, was more challenging than expected. The potentials of the discussed turbocharger technologies depend on what one wants to achieve from the application. If the aspiration is to fulfil Tier III requirements and the vessel often travels in ECA, installing EGR and using MAN Diesel & Turbo's ETB could be preferred. If the goal is to have a turbocharger which is adapted to slow steaming and achieve a better fuel economy then the authors would recommend applying a VGT, using cut-out methods and possibly two-stage turbocharging.

5.1 Method discussion

A comparison of the advances suitability was desired, but unfortunately not possible to execute due to the various types of tests and simulations that were found in the materials. The articles and papers used different simulation software and different types of two-stroke marine diesel engines. As mentioned, some tests were performed on real vessels. Even though some actual values were given it was not appropriate to compare them, since in an accurate comparison the prerequisites should be equal.

It was difficult to find information intended for the public since the topic is very specific. Several articles used in the thesis were conference proceedings from CIMAC, obtained by the thesis mentor. Attempts of acquiring further information from turbocharging companies were made, but seeing as the different technologies are sellable products, information on the techniques used in advances was sensitive. The companies referred to their product catalogues, which were viewed before requesting additional information. The product catalogues only described the benefits of the products and did not contain any in-depth details.

The CIMAC Technical Database contained all conference proceedings from the annual congresses, where turbocharging companies and working groups introduce their latest products and research that has been undergone. The database was only available for CIMAC members and guests were entitled to a restricted search. Copies of the technical papers available on the database could be obtained if a fee was paid. An attempt was made to establish contact with CIMAC, but unfortunately it was unsuccessful.

6. Conclusions

The aim of the study was to review the recent advances for marine turbocharger technologies applied on two-stroke diesel engines. The intention was to present advantages and disadvantages of advances and give an overview of which technologies would be of interest for future development. The results are shortly summarized below and prove that all of the advances are suitable for two-stroke engines, depending on the desired factors.

Two-stage turbocharging in combination with WHR, increased bmep or variable intake port height and timing, can reduce the fuel consumption whilst taking advantage of the turbocharging system's full potential, and is a solution for low speed two-stroke marine diesel engines. Although, installing a WHR system has a high first cost. Further, the cut-out methods and VGT can be useful when slow steaming, since they increase the turbocharger efficiency at low loads. The cut-out methods require a smaller installation procedure than the VGT. The hybrid turbocharger is seemingly a solution for slow steaming operations and can be used to generate electric power at high load, which makes it of interest for further development. The EGR solution is suitable for NO_x reduction when meeting the Tier III regulations are of importance. Though, the EGR is not optimal for low load operation.

6.1 For further research

For future research within the topic, creating a simulation model of a two-stroke marine engine could be beneficial, where the different turbocharging technologies are applied and tested in order to get a more accurate comparison. Another suggestion is involving the manufacturers, for better cooperation regarding specific technologies.

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