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Benefits of using an electrically assisted turbocharger to increase marine engine efficiency.

Diploma thesis in the Marine Engineering Programme

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Gothenburg, Sweden 2016

REPORT NO. SI-16/172

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Printed by Chalmers
Gothenburg, Sweden, 2016

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Abstract

This study addresses the advantages and disadvantages of installing a turbocharger with electrical assistance on board the vessel. The authors also look in this study what marine engine manufacturers view on having this kind of technology on a vessel and what future improvements that this technology can have in the shipping industry. The authors has also chosen to focus on the essential components that can be replaced or enhanced with this type of technology, with the aspect to look at what kind of energy improvements that can be made. Also deals with combining this technique with other turbocharger technologies to make it as effective as possible. In the background various techniques used on board ships in the current situation are described. Literature study and interviews were conducted to obtain the result. In order to obtain a result, assistant turbocharger technology was compared with standard components used on board today.

Keywords: Turbocharger, Hybrid Turbocharger, Electrically Assisted Turbocharger, Waste Heat.

Sammanfattning

Denna studie tar upp för- och nackdelarna med att installera en turboladdare med elektrisk assistans ombord på fartyget. Författaren tittar även i denna studie vad marina motortillverkarens har för syn på denna typ av teknik ombord på fartyg och vilka framtida förbättringar den tekniken kan ha inom sjöfartsbranschen. Författaren har också valt att fokusera på väsentliga komponenter som kan ersättas eller förbättras med denna typ av teknik, där aspekten är att titta på vilka energi förbättringar som kan görs. Tar även upp med att kombinera denna teknik med andra turboladdare tekniker för att kunna få det så effektivt som möjligt. I bakgrunden beskrivs det olika tekniker som används ombord på fartyg i dagsläget. Litteraturstudie och intervjuer gjordes för att få fram resultatet. För att kunna få fram ett resultat jämfördes assisterande turboladdare tekniken med vanliga komponenter som används ombord idag.

Nyckelord: Turboladdare, Hybrid Turboladdare, Elektrisk Assisterad Turboladdare, Spillvärme.

Acknowledgements

The authors would like to thank our mentor Ulrik Larsen, Kemal Oguz Coban at MAN B&W and Toni Stojcevski at Wärtsilä.

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Abbreviations

T/C	Turbocharger
SOx	Sulphur Oxide
NOx	Nitrogen Oxide
CO2	Carbon Dioxide
EEDI	Energy Efficiency Design Index
EATC	Electrically Assisted Turbocharger
HTC	Hybrid Turbocharger
VGT	Variable Geometry Turbocharger
SG	Shaft Generator
SFOC	Specific Fuel Oil Consumption

1 Introduction

Ono, Sakamoto, Shiraishi & Yamashita (2015) mentions that around 50% of the vessel's operating costs are fuel costs, due to this a reduction of the fuel oil consumption is an important factor for the shipping companies. It is not only the fuel oil consumption that effects the changes, also the emissions standards and energy efficiency requirements has become stricter for the shipping industry over the past years. Ship owners have been influenced by the new emissions requirements where different areas such as Emission Controlled Area (ECA) were created to keep down the Carbon Dioxide (CO2), Nitrogen Oxides (NOx), Sulphur Oxides (SOx) and particulates in the exhaust gas emissions. One way to look at the energy development is through the Energy Efficiency Design Index (EEDI), which is an important technical measure and aims for promoting the shipping companies to look at more energy efficient equipment and engines to their vessel's. The EEDI is a mark where a newly built vessels should be in energy efficiency level per capacity mile (e.g. tonne mile) for different vessel type and size segments. The EEDI level rises incrementally every five years, which will make a continued development of technology and equipment that can influence the fuel efficiency during the vessel's design phase. The new regulations will make the ship owners look at alternative ways to manage the new regulations (www.imo.org, Last accessed 2016-04-11).

The idea of connecting an electric motor to the compressor side of a turbocharger (T/C) when insufficient exhaust gas for rotating the T/C is not new. As early as the 1920's the idea was born to support the T/C with an electrical assistant. The idea evolved over the years but it was not until the 1980s the potential of having an Electrically Assisted Turbocharger (EATC) that could offer both increase low-speed torque and preventing the means of T/C-surge. EATC evolved over the years but mainly in light-duty diesel trucks and some experiments on heavy-duty engines, but no products were released to the heavy-duty engines. It was not until 2010 that the idea for the heavy-duty engines came back and in 2011 Mitsubishi released an EATC for heavy-duty engines (Jääskeläinen, 2015, pp. 7-8).

The main reason to use an Electrically Assisted Turbocharger (EATC), is to get increased air mass flow rate into the engine. At low-load the heat and pressure energy from the exhaust is not enough for the turbine to rotate the compressor to increase the boost pressure to the optimum amount in to the engine; with assistance from an electric motor a higher boost pressure can be achieved. That way more air can fill the cylinder and create a more stable running, which leads to more power output and lower the fuel consumption. As the turbocharger is already turning at a high speed there will be higher and more stable torque output as the engine speed increases (Özgür & Aydin, 2015, pp. 861-864).

A hybrid turbocharger (HTC) depends on the efficiency of the T/C, but the purpose is to deliver the right amount of air and to use the waste-heat to convert it in to electricity. Recent high-efficiency HTC can use 13% of the rotational energy from the T/C to produce electricity to the vessel and still supply right amount of air to the engine. At low load the generator on the HTC can work as an electrical motor same as an EATC. When out on a voyage a vessel is normally using a shaft generator (SG) to produce electricity for the vessel and taking its power from the main engine shaft, but with a HTC there is an possibility to decrease the SG power requirements from the main engine or even cancel it out and only run on a HTC. The HTC would then directly reduce the fuel consumption. (Ono, Sakamoto, Yamashita & Shiraishi, 2015, p 36-41).

With the help of EATC there is potential for economy savings, lower fuel consumption and emissions reduction. In the marine sector development has been absent, but there are already prototypes out in the market that have made the manufactures interested to start looking into potential to have an EATC and HTC (Ono, Yamashita and Shiraishi, 2012, pp. 29-33). With this type of technology, it is possible save weight and that is because it can replace other essential equipment's, such as auxiliary blowers and SG.

1.1 Purpose

The purpose of this study is divided in to two parts. One is to analyse the advantages and disadvantages of having an Electrically Assisted Turbocharger (EATC) or a hybrid turbocharger (HTC) instead of the conventional turbocharger (T/C). The other is to look into the benefits that can be achieved by replacing essential equipment such as shaft generator (SG) and auxiliary blower by using EATC or HTC.

1.2 Questions

The main question is:

- What are the advantages and disadvantages converting to electrically assisted turbocharger (EATC) or a hybrid turbocharger (HTC) from a conventional turbocharger (T/C)?

Sub queries to answer the main question is:

- What are marine engine manufacturers' views on having an EATC or a HTC?

- Is it possible to replace essential equipment such as auxiliary blowers or shaft generator (SG) with this technology, to achieve a better energy efficiency?

- Would this technology make any improvements to meet the environmental regulations?

1.3 Delimitations

This study is limited to a theoretical level since the authors do not have access to a laboratory, test facilities or possible field study. The study is also limited to the response from the manufacturers that the authors are going to interview, which can be a setback in the process. Since this kind of system is rare in ships and power plants of sorts, it is hard to grasp if it really is more efficient and what experience marine engineers have with this system.

The researcher limited this research to the effects on the main engine from air intake to shaft output, including auxiliary systems will be far more than necessary, more complicated and time consuming.

2 Background and/or Theory

In this chapter the turbocharger (T/C) operation and its development is presented. To get an overview of how an electrically assisted turbocharger (EATC) or a hybrid turbocharger (HTC) can improve energy efficiency, some essential components are mentioned that can be replaced or be reduced so the effect on the engine decreases. In order to cope with IMO's MARPOL Annex VI regulations for air emissions where the T/C can be affected in the process, some of the techniques used for improving the exhaust gas emissions are mentioned. There are various equipment's such as the Variable Geometry Turbocharger (VGT) that can improve the turbochargers efficiency that can be compared with EATC or HTC.

2.1 Turbocharger

The purpose of a turbocharger (T/C) is to use the exhaust gas heat and pressure energy to supply more air into the engine. With a higher air flow rate more fuel can be burned and thus more power can be produced for a given engine size. After the combustion in the cylinder the exhaust heat energy and high pressure is used to rotate the turbine side of the T/C, allowing the compressor side to rotate with the turbine and the air flow will increase in to the scavenge box and in to the engine. As shown in Figure 1, usual line up for an air path for the T/C is: compressor inlet filter - compressor - air cooler - scavenge box - cylinder inlet/valve - cylinder vent/valve -exhaust pipe - exhaust turbine - exhaust boiler - atmosphere (Nan & Yue, 2014, pp 711-714).

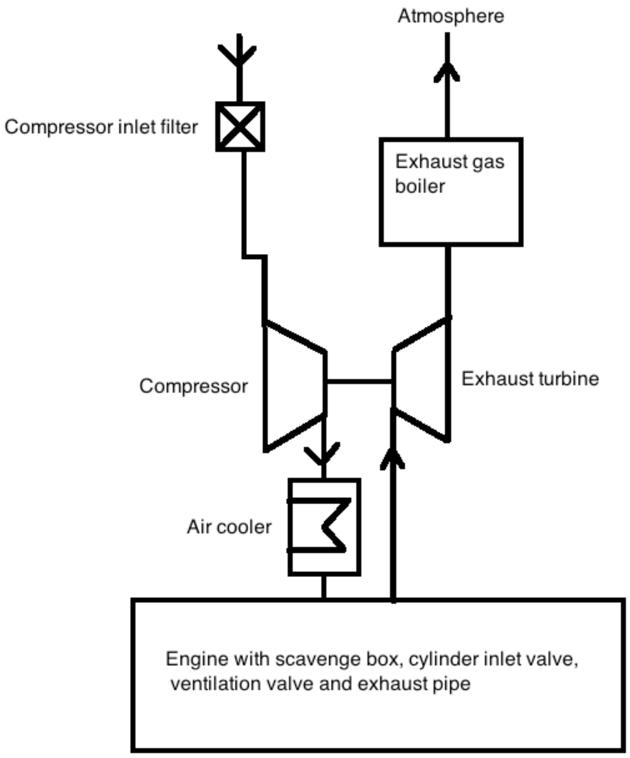

Figure 1, Example of an air patch for T/C. (Authors own figure).

It is also possible to run two T/C in parallel to each other, in order to distribute the exhaust gas between the turbines it is called twin T/C arrangement. It is most common to use this twin T/C arrangement on larger diesel engines, the reason is to be able to reduce the size of T/C and another reason is that a larger T/C can have an unacceptable transient response (Jääskeläinen, 2016).

Uriondo, Durán Grados, Clemente, Gutiérrez and Martín (2011, pp 3) discusses about the charge air's major impact on the amount of nitrogen oxide (NOx) emissions from engine. When the charge air pressure increases the temperature of the charge air will increase due to the pressure. With the increase of the charge air's temperature there will be higher maximum combustion temperature and that will make the NOx emissions increase.

2.1.1 Turbocharger-surge

Surge is a very common thing to occur in the turbocharger (T/C) and it occurs most frequently in low-speed diesel engines. T/C-surge occurs when a big mass air flow oscillation passes the compressor side and creates vibrations on the impeller and the vanes. The vibrations make the compressor not being able to run as it should, and high noises often occur from the T/C. As shown in Figure 2, Compressor surge can also occur when the T/C is running at a fixed speed, but the air flow is reducing from its design value a reason can be due to clogged air flow path and air bubbles expands in the vane diffuser or impeller, causing compressor surge. For a new T/C it is unusual that surge will appear, it is more common that surge appears when the T/C parts have been worn down due to the running hours. The result of worn parts is that the engine and T/C will be badly matched and that can lead to less air flow, higher pressure causing the surge to occur in T/C. It is not just because out of T/C that the surge occurs, but also some essential equipment such as a fuel valve, exhaust valve, etc. that do not work properly and provide higher exhaust's temperature which can lead to surge occurs (Nan & Yue, 2014, pp 711-714).

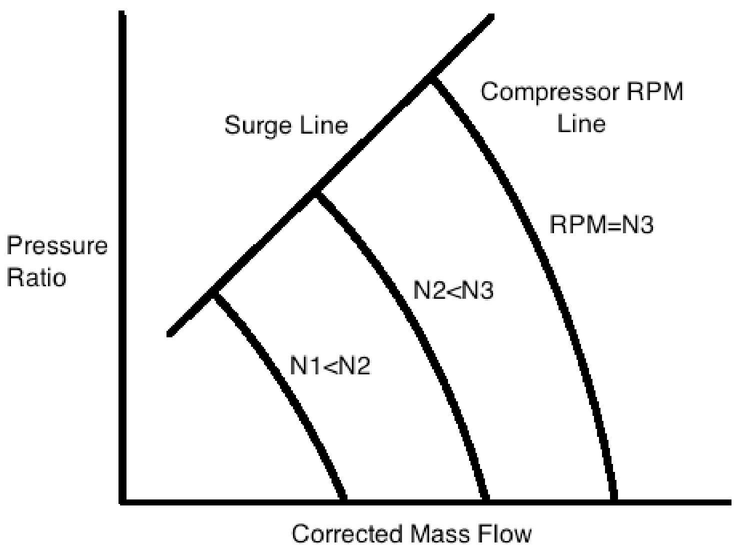

Figure 2, Performance map over compressor with different operating speeds showing the surge line, (Authors own figure).

When T/C-surge occurs it will have an effect on the emissions from the exhaust gases, because there will be a pressure drop in the charge air when the surge occurs which leads to an increase of the carbonaceous particulate emission due to improper combustion with too much fuel and too little air available (Khair & Jääskeläinen, 2015).

2.2 Electrically Assisted Turbocharger

By integrating an electric motor on the turbocharger-shaft, it is possible to use the turbocharger at low engine load. The most common way is to have the motor in the middle, between the compressor and turbine. Placing it on the compressor end of the shaft is another way of integrating it, commonly used on hybrid turbochargers (HTC) (Jääskeläinen, 2015, p. 6).

In two-stroke engines the air intakes are in the lower section of the cylinder, and since larger two-stroke engines need a massive amount of air, electric assistance for air supply is a necessity at loads below 30%. During low load operations the exhaust flow is not enough for the T/C to drive, that is where blowers activates to compensate for the loss of flow from the T/C. Electrically assisted turbocharger (EATC) have the same function as the blowers but is integrated on to the T/C, by adding rotational energy with the electric motor it is possible to produce the needed pressure for the combustion (Ono, Shiraishi, Yamashita & Sakamoto, 2015, p. 38-39).

EATC is constructed for continuous operations, while the auxiliary blowers are meant just for occasional operation. As they have a similar function by boosting the charge air, makes the EATC a good replacement. This way it can maintain and vary the speed, during low loads when the exhaust gas flow is low. With this the sufficient amount of charge air for an efficient and cleaner combustion (Krishnan & Shiraichi, 2014, p 2).

With the assistance of the EATC it is possible to lower the specific fuel consumption during high speeds but is most optimal to work during low speeds where the changes is most significant. As the specific fuel consumption is the rate of fuel consumption divided by the produced power and since the EATC produces more power during low loads, the specific fuel consumption will be lower (Özgür & Aydin, 2015, p 864).

Having electric assistance in a four-stroke engine is not as common as in two-stroke, due to the fact that the charge air is supplied via the intake which is on the top of the cylinder. When the piston is going in a downward direction, and the intake valve is open it sucks in air in the cylinder and this gives a cylinder with only fresh air. Low-load operations in a four-stroke tend to have exhaust gases with air shortage, which can lead to increased fuel consumption, decreased reliability and higher smoke production due to a poor combustion (Ono, Shiraishi, Yamashita & Sakamoto, 2015, p. 36 & 39).

2.3 Hybrid Turbocharger

Ibaraki, Yamashita, Sumida, Ogita and Jinnai (2006, pp 1-5) explains some of the advantage of developing a hybrid turbocharger (HTC) and that is improved fuel oil consumption, get a better torque from the engine and reduce the risk of turbocharger (T/C)-surge. HTC is a high-speed motor generator that works as an assistant to the engine when it is running at low load and at high load use the engine waste heat to produce electrical power.

Ono, Sakamoto, Shiraishi & Yamashita (2015) mentions that the rotational energy from the T/C is huge, accounting for up to 50% of the engine output power. By means of putting a generator to exploit the rotational energy from the turbocharger and have the opportunity to convert it into electricity, would be possible with a HTC. Depending on the efficiency on the T/C it decides how much rotating energy that will be produced with the exhaust gas energy that is coming from the engine. When the vessel is slow steaming and the engine is running at low load the generator on the HTC can work as an electrical motor same as an electrically assisted turbocharger (EATC) (Ono, Sakamoto, Yamashita & Shiraishi, 2015, p 36-41).

In the most recent years the T/C efficiency has been improved so that all the exhaust gas energy cannot be used. A good T/C can have around 10% of the efficiency that goes to waste heat, which can be used to generate electricity instead and still be able to supply enough air for the engine (Shiraishi, Ono and Sugushita, 2010, pp 53).

Being able to deliver stable voltage and the right frequency from T/C high-speed generator an AC/DC-converter is used. The converter works both ways which will make it possible to convert AC to DC making it work as an EATC and take DC from generator converting it to AC through the converter making it possible to supply electricity to the vessel (Shiraishi, Ono and Sugishita, 2010, pp 56).

With an HTC the high-speed motor generator is built into the T/C body which will make the HTC as compact as a normal T/C and no major changes is required on the main engine. Because of the compact solution of the HTC the generator can be placed in the silencer on the compressor side, which will make it easier to be able cool the high-speed motor generator with help of air, cooling water and the lubricating oil (Ono, Yamashita and Shiraishi, 2012, pp. 29-30).

2.4 Auxiliary Blowers

Auxiliary blower’s objective is to raise the air pressure and mass flow during low loads when the turbocharger (T/C) is not able to. It is more common for a two-stroke engine to be slow steaming than a four-stroke engine. A four-stroke engine also has a stroke for pushing out the exhausts, where the two-stroke has to rely on the T/C. That's why two-stroke engines need auxiliary blowers, to compensate when slow steaming and the T/C is running at low-speed. They are mostly used during departure and arrival, as it is not optimal to go on full engine load due to manoeuvring in ports. Due to short operating time of the blower the performance, reliability and energy efficiency hasn't been of much importance (Ono, Sakamoto, Yamashita & Shiraishi, 2015, p 38-39).

Now slow steaming has been trending in shipping due to the price drop of oil. As an effect of this the engine is running at a lower speed and less pressure is needed. Resulting in more operations for the blower due to the change in pressure, which makes the range for starting the blower closer. Blowers consists of a motor, centrifugal blower and runs at a constant speed and has an automatic starter. It also uses a large amount of electricity, which compared to a EATC is not very effective, while it also needs maintenance (Ono, Sakamoto, Yamashita & Shiraishi, 2015, p 38-39).

2.5 Shaft Generator

A shaft generator (SG) is a component which is driven by the shaft of the main engine to produce electricity on board the vessel when traveling at sea. The main purpose of using a SG is to reduce the fuel consumption mainly on auxiliary engines when traveling at sea. The aim is that the SG should take over all electric production that normally the auxiliary engines produces. In order to be able to produce electricity to the vessel the SG needs a certain load from the main engine, and this load depends on the type of SG that is installed on board, the load is usually between 40-105% from the main engine. As shown in Figure 3, when choosing a SG to the vessel one must take into account how much load the shaft generator will require from the engine to be able to produce electricity to the vessel. When the required load is known, it is added to the engine load diagram to check that the engine and the SG will match. This can lead to a larger engine is required for the same amount of power output for achieving the requirements that the SG needs (MAN Diesel & Turbo, 2015, pp 1-48).

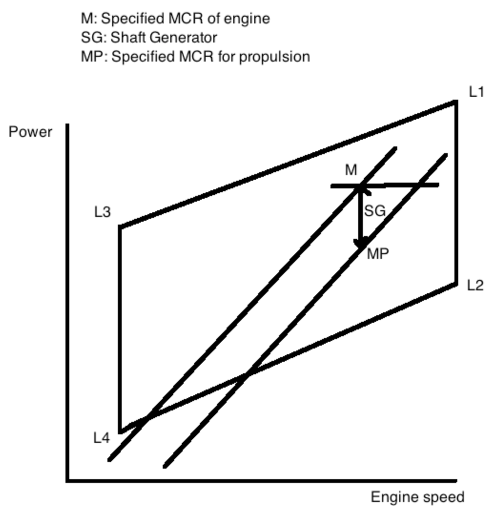

Figure 3, Example of an engine load diagram with shaft generator. (Authors own figure).

In the traditional ways the shaft generator is connected to the propeller shaft and will therefore have the same speed as the propeller. By installing a shaft generator-drive between it allows the main engine to have different speeds. Instead of fixed speed on the propeller, the drive grants control of the pitch and the desired ship speed, while still keeping a stable voltage and frequency. This enables the operations of a ship to be optimised for each route. The drive allows the SG to run in parallel with auxiliary generators if necessary. With this the benefits of lower SFOC for the main engine compared to auxiliary engines can be fully exploited. If Marine Diesel Oil were to be used instead of Heavy Fuel Oil the economic benefits would be greater (ABB, 2014).

2.6 Variable Geometry Turbocharger

There are different kinds of design to a Variable Geometry Turbocharger (VGT) such as pivoting vanes on turbine impeller, slide ring and a moving wall. All these designs have the same purpose, change the turbochargers (T/C) area and make it effective on lower loads (Jääskeläinen, 2013).

At lower speeds, the mass air flow is not as high as needed, but using a VGT the air flow can be changed and increased. This will result in larger amount of air in to the combustion during low load operations. With higher excess air in the cylinder, the combustion is cleaner and also gives more torque output. The different designs of a VGT change the flow area of the turbine and gives a better match between the engine and T/C (Stefanopoulou, Kolmanovsky & Freudenberg. 2000. p 73).

The principle of a T/C with pivoting vanes, is that the turbine impeller is surrounded by a annular ring with pivots which are controlled by an electronic actuator. They intercept the exhaust gases just before the turbine wheel, by using the pivots the flow can be controlled. The speed of the T/C is depending on the positions of the vanes, as they direct the exhausts. The actuator controls the said position, to drive the exhausts at the optimal speed to the turbine impeller. The closer the vanes are to their closed position, the higher the speed is on the T/C (Jääskeläinen, 2013, p 7-8).

On the design with a moving wall on the T/C-shaft, there is a disc which is possible to control with pneumatic control to adjust the size of the inlet to the turbine. This design will have a high mean pressure, but the forces for the actuator will be higher compared to the pivoting vanes design and a larger actuator will be needed. On the disc there are vanes that is going to fit in a crevice during operation, which needs a tight clearance and minimum contact between the two. The manufacturing costs for this can be rather high (Jääskeläinen, 2013, p. 10).

Comparing a fixed T/C with waste gate valve, which is a bypass-valve on the exhaust-side of the T/C, and VGT, a turbocharger with VGT has a higher pressure ratio, as a function of mass flow, than the fixed. The pressure ratio would be higher with the VGT. By controlling the turbines nozzle opening, it allows to control the boost pressure. This results in that a VGT can operate much closer to the surge margin to get the highest pressure, without experiencing surge as the compressor inlet changes (Jääskeläinen, 2013, p. 5).

2.7 Emissions

Emissions standards for ship industry has become stricter over the years. Air emission requirements has affected many ship owners, where special areas such as Emission Controlled Area (ECA) were created to keep down the Carbon Dioxide (CO2), Nitrogen Oxides (NOx), Sulphur Oxides (SOx) and particulates in the exhaust gas emissions. The new regulations for the exhaust gas emission will make the ship owners look at alternative ways to manage the new regulations. (www.imo.org, Last accessed 2016-03-06)

2.7.1 Emission Controlled Area

ECA directive is part of IMO's MARPOL Annex VI regulations of air emissions in the shipping industry. The emissions that are regulated in ECA areas are SOx, NOx and particulates. Ships that is operating inside and outside the ECA area is required to have fuel oil or exhaust gas cleaning unit to fulfil the requirements (www.imo.org, Last accessed 2016-03-06)

2.7.1.1 Emission regulations for SOx.

As shown in Table 1, in 2012 the global regulations for SOx emission were changed and the fuel oil sulphur content were reduced from 4.50% to 3.50%. In 2015 the SOx emissions were changed for the ECA areas and the requirement for the fuel oil sulphur content used in ECA areas were changed from 1.00% to 0.10%. In 2020 the global SOx emission will change and the sulphur in the fuel will be reduced to 0.50%, but in 2018 there will be a review how the availability of the required fuel oil and that can postpone the SOx regulations to 1 January 2025 (www.imo.org, Last accessed 2016-03-06).

Outside an ECA SOx emissions	Inside an ECA SOx emissions
4,50% m/m pior to 1 January 2012	1,50% m/m prior to July 2010
3,50% m/m on and after 1 January 2012	1,00% m/m on and after 1 July 2010
0,50% m/m on and after 1 January 2020 (2025)	0,10% m/m on and after 1 January 2015

Table 1, SOx emissions regulations inside and outside the ECA area. (Source: IMO)

2.7.1.2 Emission regulations for NOx.

NOx emissions are categorized in the "Tier I" to "Tier III" emission limit, this category is based on when the ship is built. Marine diesel engines that were built after or on 1990 were needed to have "Tier I" emission limit, in 2011 the requirement are that all ships built during or after 2011 should at least have an engine that can handle the "Tier II" emission limit and in 2016 the regulations for the requirements to have an engine for "Tier III" emission limit were needed. As shown Table 2, the Tier regulation is depending on the year the vessel was built from, what the engine maximum speed is in rpm and from that the NOx emission can be decided in g/kWh. Tier I and Tier II is a global regulation, unlike Tier III which only applies in the NOx emission control areas (www.imo.org, Last accessed 2016-03-06).

Tier	Date	RPM < 130	130 ≥ RPM < 2000	RPM ≥ 2000
Tier I	2000 (global)	17,0	$45 * n^{-0,2}$	9,8
Tier II	2011 (global)	14,4	$44 * n^{0,23}$	7,7
Tier III	2016 (NECA)	3,4	$9 * n^{-0,2}$	2,0

Table 2, Tier regulations year, engine speed in revolution per minutes (RPM) and NOx emissions in g/kWh. (Source: www.imo.org, Last accessed 2016-03-06)

3 Method

To be able to get as much substantial information as possible in this thesis other reports will be examined concerning the same subject. Also look in to what the author in the reports say about the advantages and disadvantages of using this technology. As it is not commonly used on ships contacting some engine manufacturers will be essential for their view on using an Electrically Assisted Turbocharger (EATC) or Hybrid Turbocharger (HTC) and what future plans are within this technique. Also compare data of some essential components with this technology to determine the advantages and disadvantages for retrofitting.

3.1 Literature Study

In order to get as relevant articles as possible multiple databases and keywords have been used for this article. Articles were chosen based on the content and their relevance to our study.

Keywords used both separately and together to get a broader results. The databases and keywords that have been used during the research can be seen below.

Library:
Chalmers library.

Databases:
Chalmers library, Google, Google scholar.

Keywords:
Turbocharger, Electrically assisted turbocharger, Hybrid Turbocharger, Emission, NOx, IMO MARPOL XI, Shaft generator, waste heat recovery, Variable Geometry Turbocharger, MET Turbocharger.

Selection:
When an article had been selected due to the content, it was examined more closely so the content could answer the questions and purpose. Articles was also examined whether there was interconnection of multiple components to see their results on the subject.

3.2 Manufactures Questions.

The questions for the companies were developed so they could see how companies' thoughts on the development of this technology. Also see the manufactures views of replacing essential components to this technology or the improvement of retrofitting.

In order to get relevant answers for the questions that were asked, different manufactures was contacted that are aligned with the engine or turbocharger development. The manufactures that were contacted were:

Wärtsilä, Mitsubishi, MAN B&W, ABB, Caterpillar and Honeywell.

3.2.1 Questions

1. Have your company looked in to the benefits for electrically assisted turbocharger (EATC)? If no, why?
    - What barriers do you see for this technology?
    - Would EATCs help to fulfill regulations regarding energy efficiency and emissions?

2. Do you think that the hybrid assisted turbocharger can replace the shaft generator?
    - What potential (in kW) do you think an EATC could have?
    - What influences might EATCs have on how you generate electricity on board?

3. What are your comments on electrically assisted turbocharger and engines efficiency?

4. What do you think about the systems after the turbocharger will be affected? Ex: Exhaust-Boiler and exhaust cleaning systems?

5. What are the challenges to develop a system like this to your engines?
    - Maintenance? Reliability? Price?

6. Can you see that an electrically assisted turbocharger could work with other means of aids such as SCR, EGR, VGT?

7. Is it possible to have a generator on the turbocharger on the auxiliary engine? Not necessarily an electric motor.

8. Can you see it as a stable system on the aspect of turbocharger stall and vibration?
    - Could it in fact improve your operations (reliability, fuel savings, range of using T/Cs and now blowers)?

9. When using an electrically assisted turbocharger, isn't possible to save a lot of weight and/or space?

4 Results

This chapter is divided into different parts; first part is where the articles that were used is presented, second is the comparison between Electrically Assisted Turbocharger (EATC)/Hybrid Turbocharger (HTC) and other techniques focusing on the advantages and disadvantages of EATC and HTC.

4.1 Articles

Özgür and Aydin investigated in year 2015 two different simulated engine models, one with EATC and another without, with focus on the torque curve. The results show that during low loads the model with assistance have a higher torque value from the start, it holds the high value while the speed of the T/C is increased. Whereas the engine without assistance is starting with a lower torque value and needs higher speed before it reaches the same value that the first model has. This is where the assist in the two-stroke engines has its optimal potential.

Shiraishi, Ono, Yamashita and Sakamoto investigated in year 2015 the energy improvements that can be done with converting a conventional T/C to an EATC or HTC on both two-stroke and four-stroke engines. The reason for the study is that the trend of slow steaming the vessel has become more common because of the fuel oil prices. The changes were presented in the tables and the parameters that were looked at was the required effect, total fuel oil consumption and scavenging air pressure.

Ono, Shiraishi and Yamashita examined in year 2012 the benefits of converting a T/C to an HTC and what changes that need to be made. The authors first performed a bench test where sudden load changes, the generator's temperature and T/C performance were monitored. The changes were ±10% on the transient frequency fluctuation and within 5 seconds the frequency it has recovered to ±1%. After the data were collected from the bench test, an engine T/C matching were done and sea trial were conducted where the T/C parameters were monitored in full scale. During sea trials they tested how the T/C would react when increasing and decreasing the load of the generator.

Feng, Guofeng, Bin, Guoqiang and Lin tested during the year 2012 to combine some of the popular and some new energy efficient aid for T/C, the reason was to look how they could aid each other with fuel oil consumption reduction. The T/C aids that was chosen to be combined for the test was VGT, EGR and HTC, were all three has the possibility for fuel oil reduction. The test that was conducted were computer simulated where a four-stroke engine was chosen as the test engine. The test shows that HTC working together with a VGT can reduce the fuel oil consumption even more than the HTC working with fixed geometry turbine and integrating an EGR system can give a fuel penalty, but wasted energy recovered can be improved. Final results show that with this kind of arrangement it is possible with a fuel economy reduction up to 5.5%.

Padhiyar and Sharma discussed during the year 2014 the development of the T/C and the advantages to develop an HTC to replace the conventional T/C. The author describes the improvements that can be done to the ordinary T/C by developing the HTC and what type of challenges HTC requires to achieve those parameters. The author describes another reason for keep developing the T/C and that is that the T/C is a key component for reducing the fuel oil consumptions and emissions.

Ibaraki, Yamashita, Sumida, Ogita and Jinnai explained during the year 2006 what the advantages that can come from using an HTC instead of conventional T/C. During the test an HTC prototype was developed to be able see what kind of results that could be achieved white a small scale. The result that was looked in to during the test was fuel oil efficiency, the engines torque and improvements in T/C-surge. The test was both conducted in a simulation and in a small scale. The result was presented in table where different electrically aid in kW has been used. Also the challenges of developing a full scale product was mentioned.

Shiraishi, Ono and Sugishita explained in 2010 the difference between Mitsubishi Heavy Industries conventional T/C MET83MA and their HTC MET83MAG. What is examined in the report is the advantages that will come from converting and what changes that will occur when converting to HTC MET83MAG for example weight, size and et cetera. When the generator from HTC MET83MAG is installed on the shaft the efficiency is reduced by 0.5% due to the generator. Also a generator load test was done to see how the efficiency will change on different load on the generator and not decrease lower than 60% efficiency of the T/C to provide enough air to the engine.

4.2 Comparison of different components.

HTC and EATC is a moderate easy retrofitting for the turbocharger and installation for the rest of the system. There is no need for valve controls or exhaust-gas piping, and regarding the piping there is a slight change on external dimensions. Due to the piping being as it is, the system is free from thermal and piping losses (Ono, Yamashita and Shiraishi, 2012, pp. 30).

Summary of the advantages and disadvantages that is adopted in the comparisons have been identified in the examined studies.

4.2.1 Comparing Electrically assisted turbocharger against Auxiliary Blower

Advantages:

- Reduced fuel oil consumption.
- Better reliability.
- Less electric power consumption.
- Continuous operation at any engine load.
- Improvement in T/C torque.
- Compact.

Disadvantages:

- Complicated solution
- Difficult cooling solution
- Stability.
- AC/DC converter space.
- Reduced T/C efficiency.

Shiraishi, Ono, Yamashita and Sakamoto did some tests in 2015 with slow steaming the vessel where they did compare conventional engine equipment with an EATC on both two-stroke and four-stroke engines. The test were done to see if an engine with EATC could be more fuel oil economical. Test were done with the engine running in different loads, first the engine run without EATC and used that result as a mark to compare when the engine is running whit EATC. The parameters that were put in to aspect during the test were electric power, scavenger air pressure and the reduction in total fuel oil consumption. The test on the two-stroke engine were it is more common to use auxiliary blower. The result was with the same scavenger air pressure during 20% load, the blower required 86kW power to produce the pressure which was 0.46 barg while the EATC only needed 66kW. The blowers measures where used as reference and the total flow rate change of fuel oil for both the main engine and auxiliary engine is lower by 6.7kg/h. Test were done on a four-stroke engine with 660 kW engine output, with an assist of 5.3kW at 25% engine load it was possible to reduce the net fuel oil consumption with 2.8%. Test showed that reduction on the fuel oil could be done with an EATC, although the biggest aid an EATC could have for a four-stroke engine is the black smoke reduction at the start up.

4.2.2 Comparing Hybrid turbocharger against Shaft generator

Advantages:

- Waste heat recovery.
- Beneficial at low engine load as an EATC.
- Reduced fuel oil consumption.
- Does not affect the engine load diagram.
- Improvement in T/C torque.
- Compact.
- Retrofitting is relatively simple.
- Waste gate control.

Disadvantages:

- Lower power output range.
- Difficult cooling solution.
- Stability.
- Limited to T/C efficiency.

Investigation has been done of converting an MET83MA T/C to an MET83MAG HTC. The changes that come from converting the MET83MA T/C to a MET83MAG HTC is that the weight will increase by 4.6 ton and TC will be 313 mm longer due to the generator that will be mounted to the T/C. Another change to the T/C is that the generator will require a new cooling system of fresh water and lubrication oil. Because of all these changes the HTC will be able to deliver 754 kW which is like a small auxiliary engine (Ono, Shiraishi and Yamashita, 2010).

In the year of 2012 Ono, Shiraishi and Yamashita did a sea trial with the HTC, where the goal was to see what could be accomplished with an HTC on the vessel. The parameters that were examined during the test were the T/C efficiency, power output, engine load and what will happen to the T/C when sudden load changes occur. The engine that was chosen for the test were a low-speed 7S65ME-C diesel engine and the engine was equipped with a HTC MET83MAG. The test showed that the HTC could start deliver power to the vessel at 60 % engine load and at 75 % engine load the HTC could supply sufficient power to support the whole vessels power demands.

4.2.3 Comparing EATC/HTC against VGT

Advantages:

- More fuel efficient working with VGT.
- Waste heat recovery.
- Retrofitting is relatively simple.

Disadvantages:

- Lower HTC-power per kW relation with use of fixed-T/C.
- Difficult cooling system.

Feng, Guofeng, Bin, Guoqiang and Lin (2012) did simulation tests by having a four-stroke engine with different kinds of waste heat recovery-systems, those were VGT with HTC. The purpose of using these systems is for raising the boost pressure and also lowering the emissions and improving the fuel economy. When combining VGT and HTC, the possibility to make use of the variable mass flow, have more flexibility on control and even reduce the fuel consumption even more. The tests that were conducted focused on fuel consumption and assisted power ratio, the prototype consumed 32.5L/10km. When testing HTC with a fixed-T/C the consumption raised to 32.8L/10km and had an assistance ratio of 1.05, while installing VGT together with HTC the consumption reduced to 31.2L/10km and used less assistance as the ratio was 0.83.

4.3 Interviews with the Manufacturers.

Development of Electrically Assisted Turbocharger (EATC) and Hybrid Turbocharger (HTC) is very new for large marine engines, which meant that the manufactures had very little information about the technology. But looking at the waste heat recovery is very popular but very difficult when marine engines running on varying loads that make it difficult for the manufacturer. Even if the company has not started its development to have integrated assistance in the turbocharger (T/C), there was alternative parable the manufacturers was working with. Out of those companies that were contacted, only two had the opportunity to answer the questions.

MAN Diesel and Turbo were contacted due to that the company is doing a lot of development in the marine sector. Kemal[1] mentions that MAN have not begun to look at the development of using Electrically Assisted Turbocharger (EATC) or Hybrid Turbocharger (HTC) as an aid for their MDT T/C. Kemal[1] mention that only MITSUBISHI (MET) can provide them as far as he knows.

Wärtsilä were contacted due to the company is working with both engines and a lot of new technology to improve the energy efficiency for the shipping industry. Toni[2] mentions that Wärtsilä knows about the technology but have not started looking into developing an EATC or HTC for their engines T/C. Toni[2] says “Probably in the short future when the hybrid technologies becomes more mature this will be relevant.”.

It was also mentioned that Wärtsilä has an external system that works in the same way as an HTC using the waste heat from the exhaust gases to produce electricity, but Toni[2] says "The ultimate would be to have all embodied in a single system, but as I said we are not there yet.”. But the external system has only been used in power stations, Toni[2] mentions that the reason for that is that ships rarely is running continuously above 70% engine load, but the exception would be diesel-electric powered vessels.

[1] Kemal Oguz Coban (Head of Turbocharger Promotion, MAN Diesel & Turbo) interviewed by the author 7 Mars 2016.

[2] Toni Stojcevski (Project Manager, Wärtsilä) interviewed by the author 22 February 2016.

4.4 Environmental improvements with an EATC or HTC

Energy requirements gets tougher with the years in which the vessels must comply with EEDI for the ship to be built. Slow steaming vessel proves more and more popular to meet the energy demands and in that case the T/C is required assistance to be able to run the engine at those low loads, then an EATC very handy to have for assisting the T/C. By converting a T/C to an EATC can lead to reductions in the fuel oil consumption both on the main engine and also on the auxiliary engines. Where auxiliary blowers are used an EATC can be used instead and tests has shown that it can require less power to achieve the same scavenger air pressure which can lead to fuel oil reduction in the auxiliary engines, which is presented in chapter 4.2.1. The easiest way of making reduction in the emission is to use less fuel oil that can be done by slow steaming and there an EATC or HTC can be of assistance.

With the aid of an HTC there is possibility to take advantage of the waste heat energy from exhaust gases that is not used by a conventional T/C and be able to convert it to electricity to support the vessel, making use of more waste heat than normal. With this type of technology where the T/C is working as generator at high engine load there are possibility to reduce the SG or even cancel it out as the HTC is not requiring a larger engine for the same power output and thus lower the fuel consumption and emissions. Therefor hardly any major negative impact on the engines performance will show (Shiraishi, Ono, Yamashita and Sakamoto, 2015).

5 Discussion

In the article written by Shiraishi, Ono, Yamashita and Sakamoto in 2015 has been reviewed over you can see many benefits of the EATC can replace an axillary blower. But then there is only one engine manufacturer that has released a prototype on the market yet, so it is difficult to determine the outcome with few tests. In the test comparing the Hybrid Turbocharger (HTC) and blower they tested at two different loads, 20% and 25%, where they also had two different settings on the assistance to the Electrically Assistant Turbocharger (EATC), one used less assistance and the other used more. These proved to be more efficient than the blower, concerning the consumption of fuel and usage of electricity.

An HTC proves to be very good for the waste heat recovery, although it was difficult to get broad results out of the technology as there is only one engine manufacturer which is engaged in the elaboration today. There are many benefits for HTC to replace the Shaft Generator (SG) but there is a drawback that makes it difficult for HTC to fully take SG place yet and that is the limit of power output to the T/C efficiency. A HTC is locked to what engine or T/C the engine has, as it uses waste heat energy it is depending on the amount that produces by the engine. Whereas the SG is controlling which engine that is needed for the desired electricity output and propeller power output.

The article were Feng, Guofeng, Bin, Guoqiang and Lin (2012) did tests with HTC and Variable Geometry Turbocharger (VGT) shows that having them work together would be the most optimal, but since new cooling system for the electric motor needs to be installed and controls for the VGT have to fit on the T/C it can be a tight fit. Other means of techniques in combination with HTC were tested as well but they were not as efficient as the combination of HTC and VGT. They had lower fuel consumption than most and used the less assist. Which shows that they can be a good package to have when constructing this kind of T/C. Maybe in the future this is the kind of T/C that will be the most common on all ships.

To the extent of weight saving is very difficult to say specifically how much you can save, when there is only one engine manufacturer using this technology. But the solution is very compact and does not weigh much, so with an EATC or an HTC will be able to save space by replacing auxiliary blower and reduce SG size.

The interviews did unfortunately not go as hoped, of those who were contacted only two answered. Which was a bit of a setback, but at least they shared their thoughts about using this technology. The company that we wanted answer from the most is Mitsubishi due to the fact that they are the only ones that have a HTC that is installed and is operating on a vessel. From the answer we got it did not seem as they were ready to research on this technology, but at least Wärtsilä had an external system that were similar to a HTC but was only used in power plants where the engines are running in more constant loads. When searching for information on different manufacturers websites there were not many who showed that they were investigated in this kind of integrated waste heat recovery system for the T/C. The companies that have started to look at a waste heat system are more looking in the direction of an external waste heat recovery system, which will take more space than the HTC and possibly work less efficient than the integrated system due to losses in pipe arrangement etc.

Then there are results that fuel oil consumption can be reduced by using an EATC but there is only one test on one type of two-stroke engine with a given T/C. To bring more concrete results would be to test several sizes of two-stroke engines to see how effective the technique can be at various sizes of engines. The tests also showed that the EATC could be effective on a four-stroke engine as it can assist with the black smoke reduction, it is on the pine in many ports to acquire a control of the black smoke where emissions can lead to fines.

5.1 Method Discussion

There is only one company that has a prototype out on the market for now and many of the articles from this company has been used in this study which makes it very difficult to summarize the disadvantages.

Many of the articles that we used for the comparisons were based on tests on different kinds of engines, some smaller but also marine engines. That way this report may not have the validity for being just for marine engines and maybe more in general for usage of this technology. This is because the only working HTC is constructed by one company and we did not get any contact with them, so we had to go on their papers they have published.

The questions we sent to the companies were about if the technology would be seen in a near future, how it affect other systems and the reliability of this system. Even if it would be possible to have a generator on the auxiliary engine's T/C also, as they run very often longer operations. Especially on passenger ships where the ships are in port more than others. Using HTC or some kind of generator on the T/C to be able to increase the production of electricity by every engine to the point of where an engine could be excess. This can lead to reducing one or more auxiliary engines, or maybe use them as spare in case of emergency where the other are not operational. Although the redundancy should not be affected if this were to be used.

The interviews could have gone differently as they were solely based on e-mail conversations. Many of the companies that we contacted does not have an office near our position, making it harder for us to arrange a meeting. If they were within acceptable range, it would been possible for us to visit them to make sure we got the answers we wanted.

6 Conclusions

The aim of the study was to see the possibility of converting the turbocharger (T/C) to an Hybrid Turbocharger (HTC) or an Electrically Assistant Turbocharger (EATC) and about the benefits of converting is good enough to replace essential equipment. A summary of the results given by the study:

- An EATC has been shown in the study that it can reduce the fuel consumption by 6.7kg/h and assist the engine with 20kW less power than an auxiliary blower for the same amount of scavenge air pressure. EATC is a simple and practical conversion for the T/C to improve energy efficiency. Then it may also assist a four-stroke engine but proves most effective to have on board a vessel with a two-stroke engine where it can replace the auxiliary blowers. An EATC is an ideal tool for reducing the fuel oil consumption and very practical interface as it is compact solution.

- A HTC is great to utilizing the waste heat from the exhaust gases to produce electricity to vessel. HTC can produce electricity but is limited to the T/C efficiency, making it difficult for it to replace the shaft generator (SG) but very good compliment to reduce SG effect on the engine performance. An HTC is a very compact and easy solution for the waste heat to aid the vessel with the electricity.

- EATC and HTC for marine engines is new on the market and not at a stage where most of the engine manufacturers are researching on it, but there is interest for development in the future. When there is more research on the subject.

To convert T/C to an EATC or HTC is a compact and good solution to both fuel reduction and utilizing the waste heat from the engine. With technology on a vessel with a large two-stroke engine hit will have both the possibility to remove the axillary blowers and also reduce the effect size of the SG. In a four-stroke engine it can also reduce black smoke in the startup of the engine.

6.1 Suggestions for further work

This study is the comparison to see the possibilities of an HTC or an EATC and what changes that can be made with this technology on board a vessel. What this study is not looking in to is how much this technology can optimize the waste heat recovery. A further work could be working together with engine manufacturers to see what can be done to get this technology out on the market.

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