

Exhaust gas economizer on auxiliary engines

A case study of potential savings that can be made by installing an exhaust gas economizer on an auxiliary diesel engine.

Diploma thesis in the Marine Engineering Programme

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Abstract

With more expensive bunker oil prices and much tougher environmental requirements, it is of major importance for shipping companies to reduce their consumption of fuel oil today than it ever has been before. There are many ways to lower the consumption; the most efficient would be to reduce the speed of the vessel. This study has however focused on the potential savings that could be made by installing an exhaust gas economizer for the auxiliary engine on board ships.

The reason why many ships have not installed economizers on their auxiliary engines is because the investment has not been considered necessary before. This work is primarily a case study on the vessel M/V Stena Forecaster, but can probably be seen as a general guideline as well.

On-board data from the ship and information from manufacturers has been collected, in order to calculate the steam need for the ship during the period of May 2015, as well as how much steam an exhaust gas economizer could produce during the conditions of May 2015.

The exhaust gas economizer in this study would be installed on a Wärtsilä 9L20C engine, and the economizer selected is an Aalborg XS TC7A from Alfa Laval.

The result shows the possibilities and potential savings of this investment in terms of lower fuel oil consumption for the auxiliary boilers, the environmental benefits with reduced emissions, a possible installation location and a reasonable pay-back time for the current sailing route. This can however differ widely depending on for example sailing routes and weather conditions.

An investment of this sort should be discussed having in mind the age of the ship, sailing route, and who pays for the bunker oil. In this particular case the owner does not pay for the bunker, the charter does, and therefore the investment cannot be seen as a direct profit for the owner. However, the ship could be more attractive for future charters if the overall fuel oil consumption is lower. A lower fuel oil consumption is also directly beneficial for the environment.

Sammanfattning

Med dyrare bunkeroljepriser och betydligt tuffare miljökrav, så är det av större betydelse för rederierna att minska sin konsumtion av bränsle idag än det någonsin har varit tidigare. Det finns många sätt att sänka förbrukningen; det mest effektiva är att minska hastigheten hos fartyget. Denna studie har dock fokuserat på de potentiella besparingar som kan göras genom att installera en avgaspanna på hjälpmotorn ombord på fartyget.

Anledningen till att många fartyg inte har installerat avgaspannor på sina hjälpmotorer är att investeringen inte har ansetts nödvändig förut. Arbetet är i första hand en fallstudie på fartyget M/V Stena Forecaster, men kan förmodligen ses som en allmän riktlinje.

Ombord-data har samlats in från fartyget och information från tillverkare av panna och motor har inhämtats, i syfte att beräkna fartygets ångbehov under maj månad 2015 samt hur mycket ånga en avgaspanna skulle kunna producera under maj månad 2015.

Avgaspannan i denna studie är tänkt att installeras på en Wärtsiläs 9L20C motor, och den tänkta avgaspannan är en Aalborg XS TC7A från Alfa Laval.

Resultatet visar på möjligheterna och de potentiella besparingarna denna investering kan ge i form av lägre bränsleförbrukningen för ångpannorna ombord, miljöfördelarna med minskade utsläpp, en möjlig installationsplats och en rimlig återbetalningstid för den aktuella avgaspannan. Detta kan dock variera mycket beroende på tillexempel fartygets handelsrutt och driftförhållanden.

En investering av detta slag bör diskuteras med tanke på fartygets ålder, seglingsrutt, och vem som betalar för bunkeroljan. I detta fallet betalar inte ägaren för bunkeroljan, fartygs charterern gör det, och därför kan inte investeringen ses som en direkt vinst för ägaren. Däremot så skulle fartyget kunna bli mer attraktiva för framtida charters om den totala bränsleförbrukningen är lägre. En lägre bränsleförbrukning är sammatidigt direkt fördelaktigt för miljön.

Key words

ECA – emission controlled areas

Fuel oil prices

EGE – exhaust gas economizer

Auxiliary boiler

Steam needs

Steam output

Fuel oil savings

Investment cost

Environment

Corrosion

Pay-back time

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1 Introduction

With increased demands for reduced harmful emissions from shipping, it will increase the requirements for reducing the use of fossil fuels containing sulfur that during combustion transforms to sulfur oxides. In recent decades, shipping has increased considerably, which contributed to increased emissions (Petersson, 2015). One of the ways to reduce emissions is to utilize the energy in the exhaust gas with waste heat boilers.

This study will specifically investigate what fuel oil savings can be made onboard M/V Stena Forecaster during port stays by installing an exhaust gas economizer at one of the auxiliary engines and estimate how long time it will take before the investment starts to pay off in economic terms, and show the environmental benefits of this installation. The study will take into account operational difficulties that might occur having an economizer onboard such as corrosion problems.

Typically, an Exhaust Gas Economizer is able to generate approximately 500 kg/h steam from the exhaust gas of a single 1000 kW auxiliary engine. (Greens Power, 2015)

1.1 Purpose

The aim of this study is to investigate the possibility of installing an exhaust gas economizer on the auxiliary engine on board Stena Forecaster, in order to both reduce emissions and to save money in terms of fuel oil savings.

1.2 Questions

Primary research question:

What are the possibilities and potential savings of installing an EGE on Stena Forecasters auxiliary engine?

Secondary research questions:

What fuel oil savings could be made? How much will the environment benefit on this investment in terms of reduced emissions from the auxiliary boiler? What are the installation possibilities? Might there be any operational difficulties that need to be taken into account? What would the projected payback time be in such case?

1.3 Delimitations

Restrictions to savings in fuel oil consumption with data from the month of May 2015 on-board Stena forecaster during European port stays. Calculations will be made with MGO as energy source because European ports require the vessel to run on low sulphur fuel oil. Investment cost and maintenance cost will be estimated but not further analysed in this report, since these data are difficult to predict.

Savings in fuel consumptions might be made while the ship is sailing, when the auxiliary boilers have to support the main engines economizers, like during manoeuvring or low load on the main engine(s). This will be taken in consideration but not be further analysed.

2 Background and Theory

2.1 History

Edward Green invented and patented the first fuel economizer in 1845. The purpose of the invention was to increase the efficiency of boilers of fixed steam engines for various uses. Since then waste heat from propulsion engines has been used widely, not at least for steam production on marine vessels, where economizers have been installed on the vessels main engines (Greens Power, 2015).

As engines grew larger over time the amount of heat in the exhaust gases increased until it could generate enough steam in the economizers to run a turbo-alternator that produced electricity for the ship and still have a surplus for heating purposes. Modern diesel engines have a thermal energy in the exhaust gases that is equivalent to more than 30 % of the total heating value of the fuel. The exhaust gases hold a temperature between 270 °C and 320 °C for slow two stroke engines, and 350 °C to 480 °C for medium speed four stroke engines. Modern engines have increased in efficiency to the point where heat from the exhaust gases are reduced and now enough electricity can only be generated by relatively sophisticated steam generating systems (Self, 2011).

2.2 The purpose of an exhaust gas economizer

Recovery of waste heat from the exhaust gases has a direct effect on the efficiency of the process. This is reflected by reduction in the utility consumption and costs, and process cost (Syllabus, 2015). By having economizers installed on a vessel, the vessels auxiliary boilers won't have to run as much, or not at all during sea voyages, when the main engine(s) are running, in order to maintain the steam pressure required for heating of bunker tanks, hot water and other consumers. How much the auxiliary boiler will have to run depends on the steam required, the engine load and the steam output of the economizer. During port stays however the auxiliary boiler will run continuously to uphold the steam pressure required. The auxiliary steam installation provided in modern diesel powered vessels usually uses exhaust gas heat exchanger(s) at the base of the funnel and one or perhaps two auxiliary boilers. Saturated or superheated steam may be obtained from the auxiliary boiler depending on the purpose. At sea the auxiliary boiler will act as a steam receiver for the exhaust-gas heat exchanger(s), which is circulated through it. In port it is oil-fired in the usual way (Taylor, 1996, p84).

The fuel oil consumption of the auxiliary boilers during port stays could be reduced by installing exhaust gas economizers on the auxiliary engines. The payback time for retrofits on moderately aged vessels is considered less than two years according to big manufacturers of economizers like Alfa Laval and Greens Power (Alfa Laval, 2015, Greens Power, 2015). Auxiliary engine solutions have existed for a long time but when fuel prices were lower, the waste heat from auxiliary engines seemed less important (Jespersen, 2015). Why installation of economizers on the auxiliary engines today is more important is mainly because of higher bunker prices and new environmental regulations.

2.3 New environmental regulations

In 1973, IMO adopted the International Convention for the Prevention of Pollution from Ships, today known universally as MARPOL, which has been amended by the Protocols of 1978 and 1997 and kept updated with relevant amendments (IMO, c2015).

MARPOL Annex VI, first adopted in 1997, limits the main air pollutants contained in ships exhaust gas, including sulphur oxides (SO_x) and nitrous oxides (NO_x), and prohibits deliberate emissions of ozone depleting substances (ODS). Under the revised MARPOL Annex VI, the global sulphur cap will be reduced from current 3.50 % to 0.50 %, effective from 1 January 2020, subject to a feasibility review to be completed no later than 2018. The limits applicable in ECAs for SO_x and particulate matter were reduced to 0.10 %, from 1 January 2015 (IMO, c2015).

As of 1st of January 2015 regulation 14 of the IMO MARPOL Annex VI states that all vessels sailing within the environmental controlled areas ((North American Emission Control Area, Baltic Sea and the U.S. Caribbean Sea Emission Control Area) must reduce their SO_x emissions to a maximum of 0.10 %. Ship owners are faced with a number of important decisions in terms of investment and trading if they want to do business within the future sulphur limits of Emission Control Areas (ECAs). Decisions such as running the ship on distillate fuel or installing scrubbers when operating inside ECA. The deciding factors influencing the investment decision for installation of a scrubber are the fuel cost spread and the time spent in an ECA. If the chosen solution is the fuel option it means that vessels sailing in ECAs are required to use the much costlier marine gas oil (MGO). Instead of paying a fuel premium for distillate fuel, the ship owner has the option to invest in a LNG solution or a scrubber; the latter makes it possible to use the cheaper HFO fuel. In most circumstances a conversion to LNG appears too expensive, so scrubbers could be seen as a real alternative (Bimco, 2013).

2.4 Fuel oil prices and the evolvement of environmental thinking

The crude and diesel oil prices are at this moment 2015 relatively low but this past 10 years it has been increasing and was up to a historical record as of 2008 as shown in figure 1. This is all depending on worldwide production and demands as well as politics. Fuel oil consumption is one of the highest costs for all maritime companies and therefore of utter most importance to try to reduce as much as possible (Notteboom, Vernimmen, 2008).

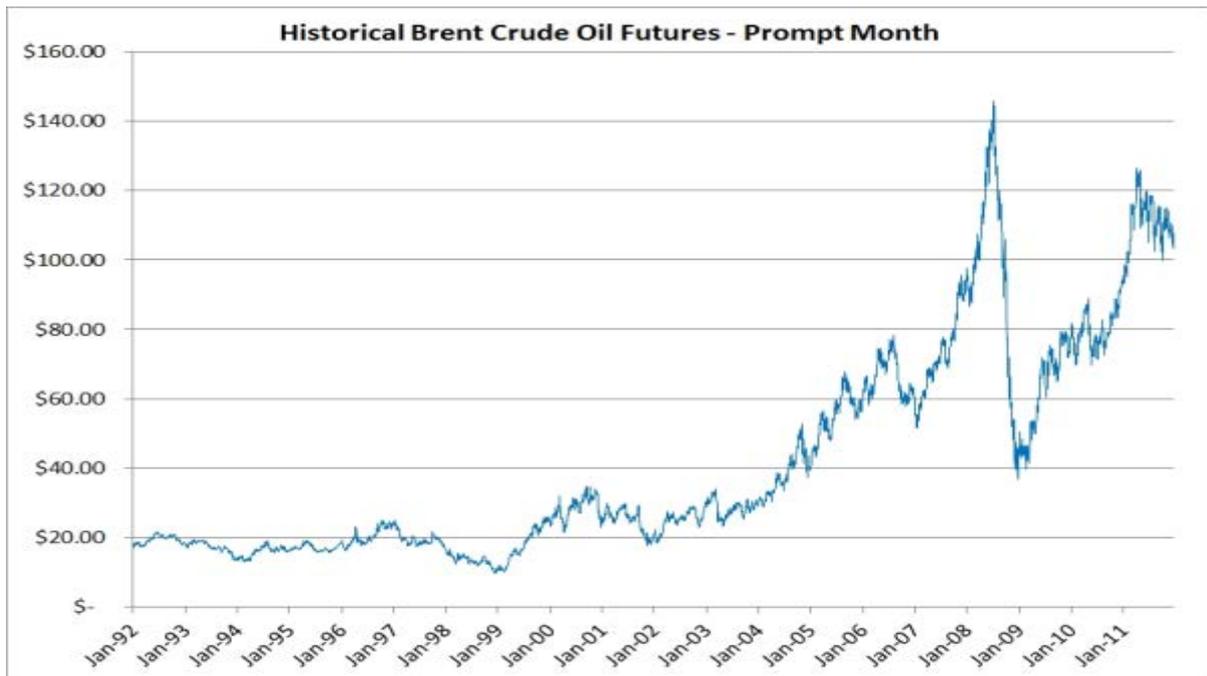


Figure 1: Crude oil prices 1992 - 2011 (Mercatus, 2011)

In the 70s emissions of sulfur was a big political question in the west. The acidification of lakes and soil was especially problematic in the Scandinavian countries. Big quantities of sulfur was transported in to the Nordic countries and in combination with a bedrock that had low buffering capacity, the acidification was a fact. Land based sulfur emissions have since then been reduced significantly through different political decisions (SMHI, 2014).

Today the land based sulfur emissions in EU are in the same quantity as the shipping emissions around Europe's coastlines. At the same time, the emission trends indicate increasing shipping emissions and the land-based emissions are predicted to roughly stay the same (SMHI, 2014). Based on these facts one can see that the most important lowering of emissions in the west that can be done today originates from shipping. SO_x are the most worrying emission but also NO_x and CO₂ are of a concern. Reducing fuel consumption onboard would help in reducing these emissions. And installing an economizer on the auxiliary engine could help in reducing the fuel oil consumption (SMHI, 2014).

Prior to the 2009 climate summit in Copenhagen the scientific journal Nature published an article written by more than 20 scientists from around the world. The article was titled "A safe operating space for humanity" and stated something that they called the planetary boundaries, including climate, stratospheric ozone, biodiversity and ocean acidification. The researchers in the journal compared the values with the pre-industrial era and established the limits of what is sustainable for the planet, so the ecosystem will not be affected too much. According to the article, the concentration of carbonate ions in the sea, measured by the average saturation level of aragonite in the sea surface today is ~ 84 %. The limit (uncertainty zone) was determined to be ≥ 80 %. The limit for carbon dioxide in the atmosphere was set to 350 ppm of carbon dioxide

with some maneuvering space, if the global warming of the planet should stay below 2 degree Celsius. The content was then at 396.5 ppm (Rockström et. al. 2009).

2.5 Description of a steam system in general

All vessels using heavy fuel oil as propellant are in need of a heating source to heat up the fuel before it can ignite. Some ships running on distillate fuel such as MGO for example does not have the need of heating.

There is different kind of arrangements onboard ships, most common is steam heating where oil fired boilers together with exhaust gas economizers produce the steam needed. In a system with an oil-fired boiler together with exhaust gas economizers, feed water is being pumped in to the auxiliary boiler, heats up and transcends into steam. The heat comes from burning fuel in a furnace inside the auxiliary boiler as well as from the exhaust gases of the main engines (Taylor, 1996).

In the auxiliary boiler, also called oil fired boiler, the produced heat from the oil ignition and combustion is transferred mainly by radiation to the water surrounding the furnace, steam bubbles are formed and rise to a steam space where water and steam are separated. Often a section of pin-tube elements is installed where the flue gases passes, working as an extended heating surface for the water. From here a steam/water mixture is discharge to the steam space where the heavier water particles separate from the steam and flow back into the water. Saturated steam can then enter the system from the steam space (Aalborg Industries, 2003). This arrangement is showed in figure 2.

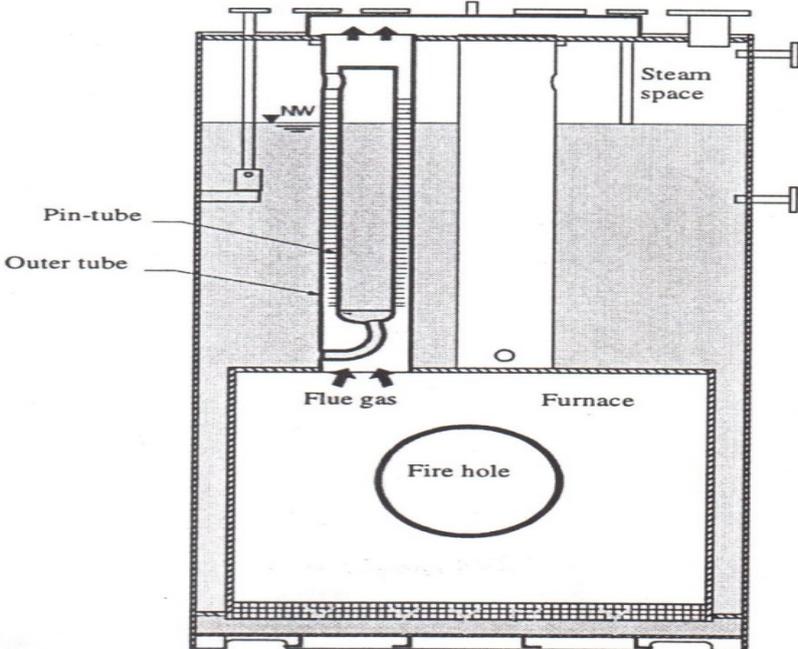


Figure 2: Oil fired boiler (Aalborg Industries, 2003)

While on voyage the exhaust gases from the main engine(s) is most often enough to produce steam in the oil fired boiler steam drum without the need of firing the oil fired boiler(s). This

means that during sailing, only the exhaust gas boilers are used for steam production and the auxiliary boilers are shut off. Exhaust gas heat exchangers make use of the exhaust gases from the main engines to produce steam. The arrangement sees to that as little as possible of the heat energy from the exhaust gases go to waste. Exhaust gas heat exchangers also goes under the name, exhaust gas boilers (Taylor, 2003).

The exhaust gas boiler works as a heat exchanger with a row of tube banks, through which the feed water passes. Hot exhaust gases streams over the tubes. In this way, just as in the case of a normal heat exchanger, the heat travels from the hot gases to the feed water converting the later into steam. A boiler drum is needed to continuously supply feed water, to receive steam and for the separation process. Generally, the auxiliary boiler drum is used for this purpose. Before the feed water enters the boiler it heats up with the help of a pre-heater fitted in the feed line, the purpose is to make the feed water oxygen free and prevent thermal shock in the boiler. Often a hot well is installed to observe possible oil leakage (Taylor, 1996).

The steam generated is not fully devoid of moisture. The steam can therefor also pass through a super heater to dry the steam so all the water converts to steam. The superheated steam then flows on in to the system. Saturated steam, which has a better energy transfer capacity or heat transfer coefficient, is the most common type of steam however. Superheated steam is the best option for running a turbine. With a superheater installed, a steam cooler and a temperature sensor control the temperature of the superheated steam. The source of heat energy to the superheater is also from the hot gases of the engine exhaust (Taylor, 1996). The steam arrangement is shown in figure 3.

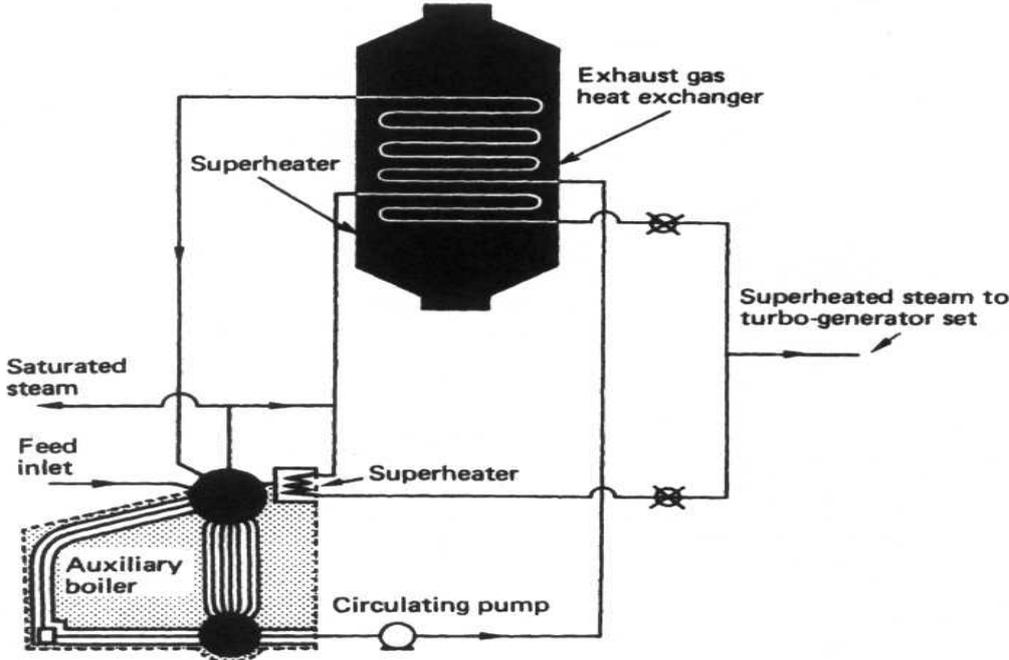


Figure 3: Steam system arrangement (Taylor, 1996)

Furthermore economizer tubes are either constructed with steel for high-pressure boilers or cast iron as in the case with low pressure industrial boilers (< 2.5Mpa/25bar), (U.Malik, 2013).

2.6 Description of the steam system on Stena Forecaster

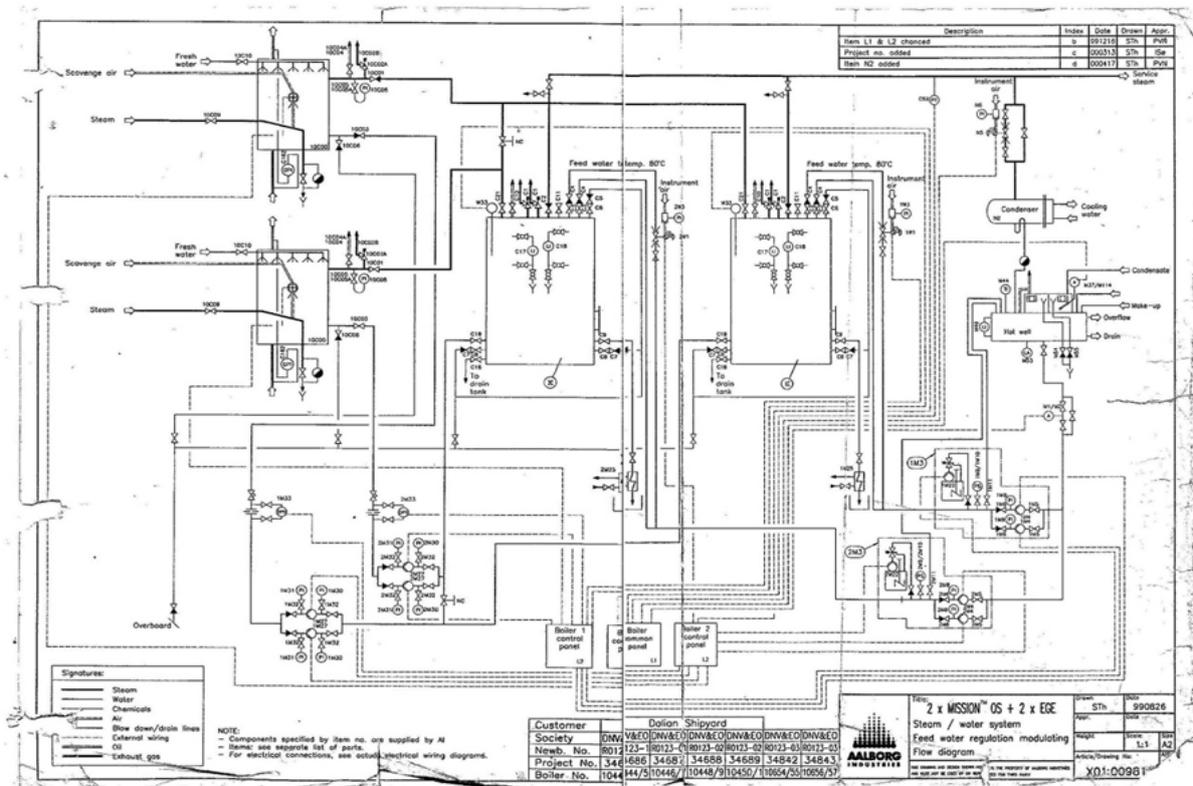


Figure 4: Steam/water system drawing, Stena Forecaster

The steam system on board Stena Forecaster as shown in figure 4, consists of two oil fired boilers model Aalborg Mission OS 3300 and three EGE (ME no 1: s economizer does not exist in the drawing, because it is a retrofit). The oil-fired boilers have a maximum steam output of 2800 kg/h each without economizers and a maximum steam output of 3300 kg/h each together with economizers, recommended operational pressure is 7 bars. The vessel has four main engines where three of them have an economizer installed. ME no. 2 and 3: s exhaust gas economizers are of the type: Exhaust gas economizer EGE 1A from Aalborg-Industries. ME no.1: s exhaust gas economizer type is: AV-6N. ME no. 1 and 2s Economizer no. 3 and 1: are located in the port side funnel and are connected to the port side auxiliary boiler, while ME no 3s economizer no. 2 is located in star board funnel and is connected to the auxiliary boiler on star board side, a simplified model is shown in figure 5.

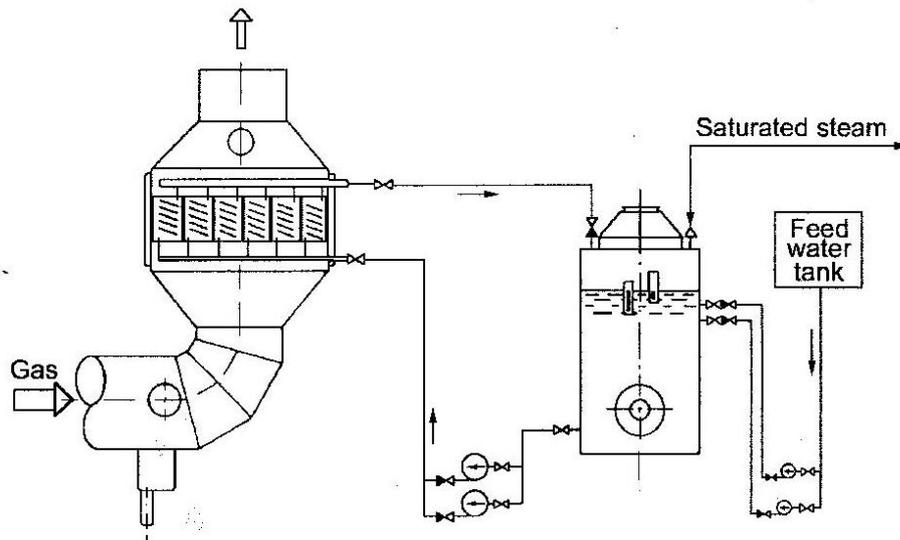


Figure 5: Steam/water system, (EGE operation manual, p3)

The economizers on ME no. 2 and 3 (economizer no. 1 and 2) are installed in Dalian shipyard, birthplace of the ship, while ME no. 1s economizer no. 3 is installed as a retrofit afterwards. Maximum steam output at a steam pressure of 7 bars from economizer no. 1 and 2 with an engine load of 100 % are 1450 kg/h while the maximum steam output with the same pressure for economizer no. 3 is 1750 kg/h. The economizers are of water tube, exhaust gas boiler type. With forced water circulation, utilizing hot gases from the main engines for transferring heat to circulating water in the economizer body. On the main steam line, after the auxiliary boilers, a condenser dumps excess steam back to the hot well, which occurs when the steam pressure is exceeding steam output set point pressure. The condenser is cooling the steam with low temperature fresh water so that it will rinse back to the hot well as condensate. From the hot well, feed pumps for the auxiliary boilers are keeping the water volume constant inside the boilers. The pressure of the feed pumps is set to 17.5 bars; the pressure is pre-set to avoid cavitation in the pumps and is high enough to make it impossible for the water to backflush. Circulation pumps are circulating the water from the auxiliary boilers through the economizers for steam production. The pumps are always running to keep the boilers heated even when the engines are not running; stand-by pumps are always ready to start if problems would occur with the running pump (Aalborg Industries, 2003)

2.7 Corrosion

Corrosion can be a problem with boilers and have to be avoided. There were several papers in the 1800s that touched the fact that corrosion was electrochemical in nature, it was first when the paper by Willis R. Whitney was published in 1903 that the idea of corrosion as an important electrochemical process took hold (Frankel, 2002).

At this time the practical use of zinc to protect boilers, condenser tubes and ships was well established but not yet understood. Nevertheless, the fact that corrosion was an electrochemical process was beginning to emerge. In the aftermath of Whitney's publication, significant studies on electrolytic corrosion was undertaken at the Massachusetts Institute of Technology (MIT). One could argue that the history of modern corrosion science was born (Frankel, 2002).

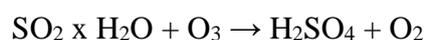
At MIT studies described the effects of dissolved oxygen as a cathode depolarizer of corrosion cells. Other studies pointed out inhomogeneity in metals caused by corrosion. At the same time a number of papers in England proposed corrosion as a direct chemical reaction. It was also recognized that corrosion could take place in other forms than rusting or pitting. During the second decade of the twentieth century, publications were made in the microbial corrosion-, corrosion fatigue-, stress corrosion cracking- and cavitation field (Frankel, 2002).

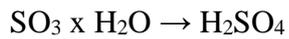
Electrochemical corrosion is when metal corrode in water, water solutions or humid environment where an electrical current is present. However, when we talk about corrosion in this paper we primarily talk about chemical corrosion. Chemical corrosion occurs when a metal reacts with a gas, steam or liquid that creates corrosion material in the contact surface that is a result of a chemical reaction (PROVEXA 2015).

2.7.1 *How corrosion works.*

In the economizer tubes corrosion can take place internally (waterside) and externally (fireside/exhaust gas side). The external corrosion comes from sulfur/moisture reaction in the economizer. The water in the flue gases condensate due to too low tube metal temperature, or the method of firing, with temperature fluctuations and different flue gas compounds as a result. This type of corrosion is avoided by keeping tube metal temperature above the dew point and tube surfaces free from corrosive deposits. The internal corrosion on the other hand, comes from wrong oxygen levels in the feed water and wrong pH levels. To avoid this type of corrosion you maintain the feed water heaters or deaerators and maintain right levels of added chemicals in the water for oxygen scavenging and pH control (U.Malik, 2013).

Under combustion in ships engines, the sulfur in the fuel oil reacts with the oxygen in the air and forms sulfur oxides (SO_x). The sulfur oxides, oxidizes to sulfuric acid (H₂SO₄), either through reactions in a liquid state or through reactions in a gaseous state. The following reactions take place when sulfur oxides encounter water (SMHI, 2014).





The sulfuric acid created is a very powerful acid. Sulfuric acid has a low steam pressure, which translates into that it is mostly in a condensate state (SMHI, 2014). The sulfur in different forms, such as SO_x and as acid affects several things, among those as follows.

The combustion of fuel containing sulfur leads to acidification, which affects people and ecosystems (SMHI, 2014).

The release of SO_x has a big impact on people's health in both a gaseous state and as particles. Studies have shown that even small reductions in sulfur dioxide leads to significant health improvements (SMHI, 2014).

Through corrosion, sulfuric acid also affects buildings and installations. Economizers' onboard ships that take heat from exhaust gases containing sulfur are therefore in danger of corrosion. In fact, investigations made by Saline Water Desalination Research Institute (SWDRI) on economizer tube failures showed that these failures mainly originated from the usage of high sulfur content fuel and the resulting acid dew point (U.Malik, 2013).

Water steam is one of the components in the exhaust gases after combustion. The water steam originates from the fuel. At a certain temperature, also called the water dew point, the water vapor in the exhaust gases condense. This normally happen between 28- and 63 degree Celsius. To avoid a condensation process, the surface in the exhaust part of the system needs to be over the dew point (Jernkontoret, 2009).

In exhaust gases, containing sulfur, sulfuric acid vapor might get created. This happens in the span of 200 to 560 degree Celsius. These sulfur acid vapors can condensate to sulfuric acid and this normally happens in the span of 115- and 138 degree Celsius, this is called the acid dew point. The acid dew point is considerably higher than the water dew point (Jernkontoret, 2009).

Condensation of sulfuric acid is the main reason for corrosion attacks in economizers' surfaces that is in contact with cold exhaust gases. The corrosion is most intense in the span of 20 to 50 degree Celsius below the acid dew point. If the temperature decreases even more, the water vapors will also condensate. This results in a larger amount of low concentrated sulfuric acid solution, together with SO_2 and CO_2 gases that also works as corrosive acids. This is the reason why there is two different corrosion maximum to consider when you talk about low temperature corrosion, namely the water dew point and the sulfuric acid dew point (Jernkontoret, 2009).

HFO and MGO contains sulfur, but fuel containing less sulfur then 1 % decrease the corrosion problem significantly. The corrosion risk the sulfur represents can be reduced by adding MgO , MgCO_3 or dolomite. Generally, one avoids corrosion through simply holding the surfaces at a higher temperature then the dew point (Jernkontoret, 2009).

Sulfur corrosion most often shows as a material thickness declination that spreads evenly over the surface. It also happens that the corrosion shows as pitting that makes holes, but in those cases the reason mostly is material failure (Jernkontoret, 2009).

2.7.2 Case studies on corrosion

Studies have been made on the failure of economizer tubes that involved acid dew-point corrosion in boilers. One paper made by Anees U. Malik and companions points out that boiler failure may be associated with waterside corrosion, fireside corrosion, overheating, stress rupture, pitting, erosion or fatigue (U.Malik, 2013).

Sulfuric acid (H_2SO_4) dew-point corrosion or cold end corrosion is a quite common occurrence in boilers running on fossil fuels and sulfur plays an important role in these attacks. The H_2SO_4 dew point corrosion is so severe in some cases that it inflicts catastrophic failure of the boiler (U.Malik, 2013).

There were three case studies made in the U. Malik paper as follows.

Case study 1:

The plant had been in service for 4 years at the time of failure. Corrosion took place at and around a weld on the tube. On one side of the tube macro pits, pinholes and holes was showing. This resulted in feed water leaking to the fireside. This is a result of corrosion by sulfuric acid (H_2SO_4), which formed by condensation of SO_2 and water vapor at a temperature below the acid dew point. The fact that one side was more corroded was probably because of the design and location of the tube wall that made more deposits from the flue gas accumulate and take the corrosion attack one-step further with a reaction between vanadium oxide and iron sulfate. The weld was the weak point in this case. The conclusion was that the main cause of economizer failure was due to operation near or below the sulfuric acid dew point. The simple solution is to run the economizer above the acid dew-point with a safety margin

Case study 2:

A boiler tripped in a power plant due to tube failure in the economizer. A rupture measuring 0.28 cm on a 145 cm tube was found in the shape of a fish mouth. The original thickness of the tube was 2 mm but was found to be reduced to 0.25 mm. The corrosion activity found to be concentrated on the outer fireside. The inside with the feed water had nominal corrosion. Large deposits of corrosion products, rich in sulfur and significantly rich in vanadium were found on the outside of the tube. The conclusion drawn was that a relative low temperature on the feed water, initiated a H_2SO_4 dew-point attack because of low temperatures on tube surface on the fireside. External deposits on the tube furthermore helped lowering the tube metal temperature and aggravated the acid condensation on the tubes. Three different countermeasures were outlined from this. First increase the feed water temperature, secondly to reduce the sulfur content in the fuel to a minimum and last to have an efficient soot blowing system.

Case study 3:

Two economizer tubes in a boiler in a power/water cogeneration desalination plant were leaking. The plant normally operated in conjunction with a turbine generator. The feed water temperature of the boiler was 195 Celsius with the turbine in service, but only 125 Celsius without the turbine. According to workforce at site, the plant operated without the turbine 8 times. This temperature drop on the feed water initiated a sulfuric acid dew-point attack on the inlet side of the economizer tubes where the feed water had its lowest temperature. The corrosion was around two weld joints, which is the most accessible sites for corrosion if the conditions is favorable. Again, a combination of sulfuric acid dew point and deposits on tubes caused the inlet tubes thickness to decrease due to sulfuric acid corrosion. If a plant has components that affect the feed water temperature to critical points in different operation modes, this should be monitored and the feed water temperature rose if necessary. As always, a fuel with low sulfur content is to prefer.

2.7.3 Prevention of corrosion onboard Stena Forecaster

On-board Stena Forecaster the main engines have existing exhaust gas economizers as described earlier. Figure 6a, 6b shows an inside view. Picture 6a illustrates the lance that cleans the economizer through a steam and air purge. This removes external deposits on the water tubes that can be outlined inside the heating flanges in picture 6b. This maintenance equipment also increases the efficiency of the heat transfer and thus the efficiency of the steam production. The flanges on the tubes in the picture furthermore increase the heat extraction from the flue gases to the water inside the tubes (Aalborg Industries, 2003).



Figure 6 a: Soot blower inside EGE, b: water tubes with flanges, Stena Forecaster

To avoid a scale buildup inside the water tubes of primarily magnesium and calcium, there are several different feed water treatments to choose from. On Stena Forecaster Drewplex AT boiler water treatment is used. The solids in the water which is treated by the additives need to be blown down from inside the boiler to prevent large sludge deposits to build up in the system.

Oxygen in the feed water, which always is present in some extension, need to get reduced as much as possible to reduce corrosion inside the tubes. If left untreated, oxygen in the feed water

can cause severe pitting in system tubing, especially in the low temperature pre-boiler section. Example of a system can be seen in figure 7 (Drew Marine, 2003). Drewplex OX corrosion inhibitor is dosed in the feedwater onboard Stena Forecaster to prevent this. By continuous testing of feed water onboard, dosing can be optimized to prevent dangerous levels of oxygen, magnesium or calcium. Together with purging of the exhaust gas economizer the system keeps healthy and functional.

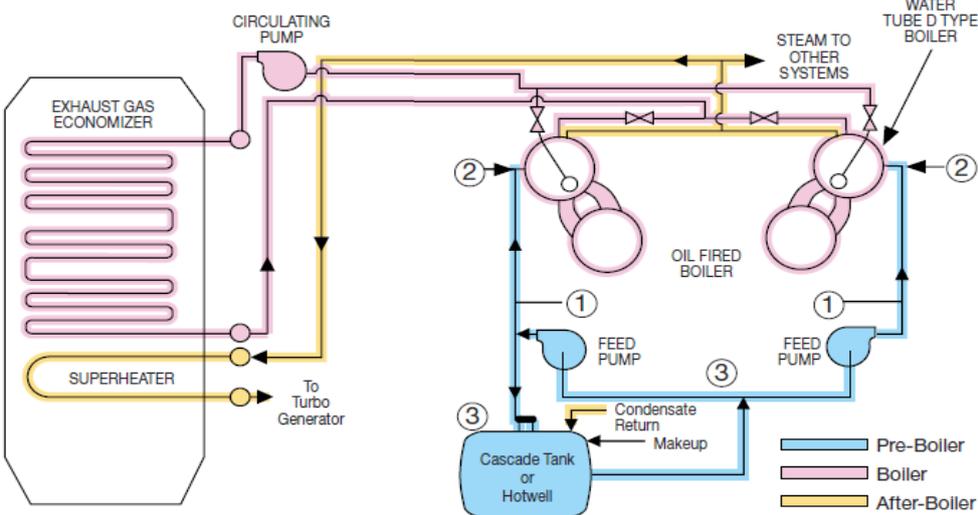


Figure 7: Example of economizer system, (Drew Marine brochure p. 3, 4)

3 Method

During the construction phase of the work, the choice of method was to do a case study on board an active merchant vessel sailing with a Swedish flag. The chapter will highlight the choice of method and how the literature was chosen. The chapter will also make aware of the email conversation with the companies that were of importance, as well as the management of calculations that led to the result.

3.1 Case study

To be able to give a picture and understanding of what savings that might be made with an exhaust gas economizer installed on a vessel's auxiliary engine, the group chose to do a case study on board the vessel Stena Forecaster. The ship was selected because one of the group's members is already working on-board as an engineer and fuel savings are of a major importance for the company in question.

The availability of relevant vessel data and already established contacts with manufacturers was of great importance. Exhaust gas economizers installed on vessels main engine has already been an obvious equipment on most commercial vessels for decades, so the group chose to focus on why it has not been as obvious to install these on auxiliary engines and how long time it would take to recover the investment cost for a retrofit on the specific vessel.

According to (Yin 2003, p. 23) case study is “an empirical inquiry that investigates a contemporary phenomenon within its real-life context, especially when the boundaries between phenomenon and context are not clear”. The underlying idea for case research is said to be the many-sided view it can provide of a situation in its context. The intense observation made in case studies gives opportunities to study different aspects and put these in relation to the environment where they operate (Halinen and Törnroos, 2005).

Case studies have an excellent clarification of an instance in "its real life context" which means that this method: works realistically; can explain details articulately; can avoid some concerns of theoretical analysis (Alnaim, 2015).

3.2 Collection of data

The majority of data collected for this study came from the ship's own equipment manuals on board, as well as relevant data downloaded from the Internet. Contact with manufacturers has been important in order to get a reasonable result and contact with the shipping company has also been of great importance in the discussion of the probability of this installation.

The web-based sources have been carefully analyzed to demonstrate the relevance, in a scientific way, but also in accordance with its age. The relevance of data gathered on board the ship, from manufacturers and information taken from websites like IMO was considered to be very high.

Operating Data from Stena Forecaster was collected during a period of 4 weeks when one of the group members was signed on as a crew member.

3.3 Calculations

The calculations are the framework of the thesis. To reach the result of the payback time for the installation of this kind, it was necessary to know the steam output a new exhaust gas economizer could give as well as the steam demand of the vessel during the given period. At the same time, to be able to compare the calculations with credible data, emails were sent directly to the manufacturer for both engine and boiler.

The theoretical calculations of the exhaust flow were also compared with test equipment on board to strengthen the results. For the calculations, existing formularies was used as well as the data that was considered necessary. The calculations are explained bellow and summarized in appendix: calculations.

3.3.1 Exhaust gas flow

In order to estimate possible steam production and choice of economizer, the exhaust gas flow from the engine must be calculated. The mass flow of exhaust gases is calculated by multiplying the mass flow rate of fuel injected into the cylinders with the actual amount of exhaust gases.

To know the actual amount of exhaust gases, the theoretical air requirement is determined in order to get the actual air requirement and in turn the excess air. With knowledge of the excess air the theoretical amount of exhaust gas is determined, an in turn also the actual amount. This is done with the following formulas:

Theoretical air requirement

$$a_t \frac{kg\ air}{kg\ fuel} = \frac{32 + 3.76 * 28}{100} * \left(\frac{c}{12} + \frac{h}{4} + \frac{s}{32} - \frac{o}{32} \right)$$

a_t = theoretical air required

c = carbon content of the fuel (molecular weight %)

s = sulphur content of the fuel (molecular weight %)

h = hydrogen content of the fuel (molecular weight %)

o = oxygen content of the fuel (molecular weight %)

f = fuel moisture (molecular weight %)

For most combustion calculations, it is sufficiently accurate to use integer molecular weights. The error incurred may easily be evaluated for a given reaction and should usually not be of concern (Weston, 2015).

Actual air requirement

$$a_a = a_t * n$$

$a_a = \text{actual air required} \left(\frac{\text{kg air}}{\text{kg fuel}} \right)$

$a_t = \text{theoretical air required}$

$n = \text{air factor}$

Excess air

$a_e = a_a - a_t$

$a_e = \text{excess air} \left(\frac{\text{kg air}}{\text{kg fuel}} \right)$

Theoretical amount of exhaust gas

$g_t = a_t + \left(1 - \frac{a}{100} \right)$

$g_t = \text{theoretical amount of exhaust gas (kg exhaust gas / kg fuel)}$

$a = \text{fuel ash (molecular weight \%)}$

Actual amount of exhaust gas

$g_a = g_t + a_e$

Two different operating modes were compared for the engine. One where the engine was running with an average load of 45 %, which is the actual average load of the auxiliary engine on-board Stena Forecaster. In the second mode, the engine runs with an average load of 75 %. This is to show the possible payback time with a higher load as well to compare these two.

The average load and fuel oil consumption for the period of 04 may 2015 – 21 may 2015 on board Stena Forecaster during European port stays was 700 kW and 1400 Amps, the average consumption was 150 kg/h diesel oil (Stena Forecaster, 2015). To determine the fuel oil consumption of the engine running at 75 % load, Wärtsilä test bed, BISO result calculations was used. The mass flow of exhaust gases could then be determined.

Mass flow rate of exhaust gas

$m_e = m_f * g_a$

$m_e = \text{mass flow rate of exhaust gas}$

$m_f = \text{mass flow rate of fuel injected into the cylinder}$

$g_a = \text{actual amount of exhaust gas}$

3.3.2 Choice of economizer and steam output

Together with the mass flow rate of exhaust gases information about the average temperature after the turbo charger was needed before a mail to Alfa Laval could be sent to get information about what economizer that would be best to install as well as estimated steam output. The vessel uses a steam plant from Aalborg-Industries who is owned by Alfa Laval and therefore the choice of Alfa Laval was made (even though other manufacturers do exist). The best

economizer for the job with an estimated steam output and cost information was obtained from Alfa Laval:

Exhaust gas economizer:	Aalborg XS TC7A
Steam output, engine running 75%:	400 kg/h (Alfa Laval)
Steam output, engine running 45 %:	300 kg/h (Alfa Laval)
Unit price:	45 000 EUR (Alfa Laval)
Installation cost:	44 500 EUR (Alfa Laval)
Total investment:	89 500 EUR (Alfa Laval)

3.3.3 The steam demand and possible fuel oil savings

The steam demand on-board the vessel was calculated on the existing oil fired boiler Aalborg Mission OS 3300.

The steam output is calculated by the formula:

$$n_p = \frac{S * (h_s - h_{f_w})}{F * H_i}$$

n_p = efficiency of boiler

S = steam output $\left(\frac{kg}{s}\right)$

h_s = enthalpy of steam output $\left(\frac{kJ}{kg}\right)$

h_{f_w} = enthalpy of feed water to boiler $\left(\frac{kJ}{kg}\right)$

F = fuel consumption $\left(\frac{kg}{s}\right)$

H_i = fuel calorific value $\left(\frac{kJ}{kg}\right)$

The efficiency of the boiler depends on the ability of the burner system to provide the proper air to fuel mixture throughout the firing rate (Clever Brooks, 2010). With knowledge of the ships steam demand and the possible steam output from Aalborg XS TC7A the fuel oil savings could then be calculated and the projected payback time estimated.

4 Result

The possibilities and savings of installing an EGE on Stena Forecasters auxiliary engine could as this study shows be a good investment. The fuel oil consumption would be lower for the auxiliary boilers, the environment would benefit in terms of lower harmful emissions because of the lower fuel oil consumption. An installation location proposal for the EGE is presented below, and should be possible, this has however not been analysed further. Operational difficulties should not be of a concern and the pay-back time is as detailed below, reasonable.

4.1 Fuel oil savings

With EGE installed on the auxiliary engine the fuel oil consumption is lower for the auxiliary boilers. In appendix: Calculations, this is detailed and the result is:

Fuel oil savings, 75 % load: 22.3 % less fuel oil = 26.8 kg/h less fuel oil

Fuel oil savings, 45 % load: 16.7 % less fuel oil = 20.0 kg/h less fuel oil

4.2 Environment

Less fuel oil means less harmful emissions such as sulfur, nitrogen oxide and carbon dioxide. Taken from the exhaust gas analysis onboard and from bunker oil test protocol, the emissions from the combustion of every liter of MGO contain approximately 10 % CO₂, 80 ppm NO_x and 0.1 % sulfur. With between 16 – 22 % lower fuel oil consumption for the auxiliary boiler with an EGE installed on the auxiliary engine the environment would benefit greatly.

4.3 Installation

The exhaust gas economizer, type Aalborg XS-TC7A, that can be installed on Stena Forecaster is an all-welded vertical smoke tube exhaust gas economizer with forced water circulation that is intended to operate in conjunction with the steam drum of the oil-fired boiler, but it is possible to install the economizer with a separate steam drum as well.

In starboard side of the engine room, the auxiliary engines are located. This is beneficial if an installation of one or two economizers on the auxiliary engines should be a reality. With only one economizer from the main engines fitted, the space is enough for installing one more from the auxiliary engines.

The best idea of installation could be to remove the AE silencer and install the EGE in that place. The silencer can be placed further up in the funnel, but most probably, it is not needed, which will save time and money during installation. This installation would be appropriate to plan for the upcoming 5-year survey, but it is also most possible that it can be installed at sea.

Other than the cost of the unit itself, circulation pumps and piping is needed, boiler valves, safety valves and electrical components. The equipment cost and installation cost is hard to

predict. A retrofit example calculated by Alfa Laval costs around 44 500 EUR plus the equipment cost of 45 000 EUR for a total of 89 500 EUR (Alfa Laval, 2014).



Figure 8: Auxiliary boiler location, Stena Forecaster

Panorama picture taken with a Samsung Galaxy S5 Mini, it shows the location of the auxiliary boiler together with the auxiliary engine silencer.

4.4 Operational difficulties

The exhaust gases from the Wärtsilä (9L20C) engine is estimated to hold a temperature of 350 Celsius in the inlet of the WHR economizer and 213 Celsius in the outlet when running the engine on 75% with a pressure drop of 102 mmWG. The same figures for a load of 50 % on the engine are 360 Celsius in the inlet and 209 Celsius in the outlet of the economizer with a pressure drop of 53 mmWG. The feedwater temperature is expected to hold around 90 degree Celsius.

Since the auxiliary engine will run on both HFO and MGO, sulfur acid vapor will be present. Since the sulfuric acid dew point lies between 115- and 138 degree Celsius it's important to hold the tubes clean to prevent sulfuric acid attacks on the flue gas side. With clean tubes the temperature should not go much lower than the lowest outlet temperature of 209 degree Celsius. Same kind of cleaning arrangement as for the ME EGE, a steam/air lance for purging, on the auxiliary economizer will remove ash and other deposits that may lower tube metal temperatures and instigate a corrosion attack.

Maintenance for this system is mainly overhaul of the pumps, cleaning of the economizer and corrosion preventive chemicals added to the feed water. Man-hours for cleaning the equipment are rarely seen as a direct cost, maintenance and spare parts for the pumps is.

As long as maintenance of the installed economizer is followed no operational difficulties with the economizer, type Aalborg XS-TC7A, is to be expected.

4.5 Payback time

<i>Investment</i>	
<i>Equipment cost, EUR</i>	<i>45000 EUR</i>
<i>Installation cost, EUR</i>	<i>44500 EUR</i>
<i>Total investment, EUR</i>	<i>89500 EUR</i>
<i>Savings, 75 % load on MGO</i>	<i>14.2 EUR/hour</i>
<i>Savings, 45 % load on MGO</i>	<i>10.62 EUR/hour</i>
<i>Running hours required to pay back: 75 % load</i>	<i>6302 running hours</i>
<i>Running hours required to pay back: 45 % load</i>	<i>8427 running hours</i>

Table 1: Payback time results

The average hours in port per week during the period of 4 of May 2015 – 21 of May 2015 were 50 hours. Of this 50 hours, 23 was spent in European ports with the auxiliary boilers running on MGO, the remaining 27 hours was spent in north Africa running on HFO.

With a hypothetical running time in port of 50 hours per week, running on diesel, the payback time would be:

$$\text{Payback time, 75 \% load} = \frac{6302}{2600} = 2.4 \text{ years}$$

$$\text{Payback time, 45 \% load} = \frac{8427}{2600} = 3.2 \text{ years}$$

5 Discussion

5.1 Result discussion

To determine the probability of a future installation of this system, mail correspondence with Stena RoRo has been done.

The theory of this thesis relies on certain estimates where various losses have not been taken into account. The result can therefore not be considered 100% accurate. However, the result gives a good picture of the approximate payback time for the investment of installing an exhaust gas economizer on the auxiliary engine. The thesis also shows the environmental benefits an investment of this nature could provide as the fuel consumption is reduced for the auxiliary boiler.

In the case study of installing an economizer on Stena Forecaster the payback time should not be more than 3.2 years for the current sailing route. This is only calculated by the time in port for the vessel during a short period of time. The installation cost can always be much higher than expected. As the system has not yet been tested on this vessel in particular, the maintenance/running in costs could be high. No calculations in savings has been made with respect of the running hours of the auxiliary boilers when the main engine load is too low to generate enough steam in the main economizers to support the steam needs onboard. This should also be taken into account when deciding to invest in the equipment or not.

Another thing to have in mind is the new environmental emission controlled areas and future sailing routes. A new route inside ECA will obviously set stricter emission requirements for the ship, and in the case of running the engines on for example MGO or methanol, the steam demand will be much lower. However, as an example, both of the sister vessels, Stena Forerunner and Stena Foreteller who are sailing inside ECA, has decided to install scrubbers for cleaning the exhaust gases instead of changing the fuel. This means that the vessel still will run on HFO. In this case the fuel oil still has to be heated and the steam output will be more or less the same. Stena Forecaster is not affected by the new regulations as of today, but it is worth having in mind a future change of route inside ECA.

RoRo vessels often has a very tight schedule and are most of the time running at full speed, but a major money saver today is to reduce the speed of the vessels, which might force the auxiliary boilers to run during voyages as well. There is also the matter of weather conditions to keep in mind. For instance the sister ships which are sailing up in the Baltic Sea like Stena Forecaster used to do, have a higher steam requirement especially during winter time when temperatures can drop to minus 30°C.

However, Stena Forecaster is an old ship; most likely, she will not be sailing for more then 5 – 10 years more. At least not as a member of the Stena RoRo fleet, with this in mind the investment might not be worth it after all.

On new built ships, on the other hand, it would most likely be a very good investment. Both Alfa Laval and Greens Power, two major manufacturers of exhaust gas economizers, have in recent years, installed this system on many vessels worldwide. Looking at the payback examples calculated by them, it sure seems like a very good investment.

In the case of Stena Forecaster, the owner does not pay for the bunker; the charter does, so the investment can't be seen as a direct profit for the owner. However the vessel could be more attractive for potential charters if the overall fuel oil consumption is lower, but is the investment worth it?

The human impact on nature is now scientifically proven. Nitrogen oxides and sulfur dioxide from the burning of fossil fuels react with other substances in the air to form acid, which falls on Earth as rain, fog, snow and dry particles and causes acidification of the oceans. The burning of fossil fuels also increases the amount of carbon dioxide in the atmosphere unless the biomass is allowed to regrow and re-absorb the same amount of carbon dioxide. A high content of carbon dioxide in the atmosphere increases the earth's global warming.

Whether or not we know exactly what will happen with the environment in the future, the risk that we will have a negative impact on the earth's climate is too large to be ignored. Reducing emissions from shipping in all possible ways is perhaps no longer a question of company's economical gain but rather a question of retaining the planet as we know it, Holocene.

5.2 **Method discussion**

When the discussion of a paper is about the methodology of the paper, the positive and negative aspects of the method as well as the validity and reliability is being discussed.

Validity is about using the right thing at the right time, reliability is all about reliability. These concepts are perhaps most useful in quantitative studies, but is also often used in qualitative studies. In a study with a quantitative approach, selecting a data collection method with a known and acceptable validity and reliability for the purpose you want to reach is often done before the data collection starts. In a study with a qualitative approach, you continuously work with the validity and reliability throughout the project. This paper is of the more qualitative sort (Nahid Golafshani, 2003).

The needs of today for reducing fuel oil consumption as well as emissions are of greater importance than back in the days. By showing this in the background, the purpose of this paper is better understood. Possible equipment problems are of a major concern before an investment of this type should be considered and is therefore illuminated. The result should furthermore be reliable.

In order to get a reliable result the case study was a satisfactory method of choice. A survey would be difficult to implement since it would require much access to historical documents as well as contemporary material from vessels that already installed exhaust gas economizers on their auxiliary engines, information that would not be in direct access. The case study simply gave the opportunity to make use of many different methods instead, in order to obtain the results.

The biggest disadvantage is however the lack of existing information about the benefits this has given companies who already have installed this type of steam system on board their vessels to compare with. This could however be solved with a survey.

The hope was that this study would personally give us useful lessons on the subject in question. Hans Eysenck (1976:9) sums up case studies as a research method: "Sometimes we simply have to keep our eyes open and look carefully at individual cases, not in the hope of proving anything, but rather in the hope of learning something!"

6 Conclusions

By installing an economizer on the auxiliary engine on the case-study-ship the fuel oil consumption will be lower for the auxiliary boiler, approximately 22.3 % running at 75 % and 16.7 % running at 45 % for the current sailing route. The installation possibilities are good and if the manufacturer's maintenance manual is followed no unexpected operational difficulties should occur.

The uncertainty about future sailing routes and the ship's age are two decisive factors not to invest in this system, the key reason is that the ship owner in this case does not pay for the fuel and therefore this investment will not be a direct profit for the owner. If the fuel would have been paid by the owner, the estimated payback time for the owner is no more than 3.2 years with the current sailing route.

However today's understanding of the human impact on the environment and the importance of keeping the greenhouse gases at the lowest possible should be reason enough to invest in any equipment that will work in the planet's best interest.

Decreasing of fuel oil consumption decreases hazardous emissions such as SO_x, NO_x, CO₂ and other harmful emissions that affect the environment, people's health, buildings and installations negatively. Therefore an investment in an EGE does not just save money by lowering the fuel oil consumption; it also decreases the environmental impact and increases people's health.

Future research could be done with methods that are more precise and with more background information from the owner, manufacturers, entrepreneurs and shipyards. The environmental aspects could also be further analyzed.

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Appendix

Calculations

Theoretical air requirement

$$a_t \frac{kg \text{ air}}{kg \text{ fuel}} = \frac{32 + 3.76 * 28}{100} * \left(\frac{c}{12} + \frac{h}{4} + \frac{s}{32} - \frac{o}{32} \right) \approx 14.4 \frac{kg \text{ air}}{kg \text{ fuel}}$$

a_t = theoretical air required

“To burn 1 kg of diesel oil, the theoretical air requirement is 14.4 kg air.” (Andersson, 2013)

Actual air requirement

$$a_a = a_t * n = 14.4 \frac{kg}{kg} * 2.5 = 36 \frac{kg}{kg}$$

a_a = actual air required $\left(\frac{kg \text{ air}}{kg \text{ fuel}} \right)$

a_t = theoretical air required

n = air factor

“Diesel engine air factor is between 1.5 and 2.5” (Gabielli, 2015)

The air factor was also tested with Testo equipment on board the vessel.

Testo air factor result with an indicated load of 900 kW = 2.5



Figure 9: Wärtsilä 9L20C Testo 330-1 air factor result

Excess air

$$a_e = a_a - a_t = 36 \frac{kg}{kg} - 14.4 \frac{kg}{kg} = 21.6 \frac{kg}{kg}$$

Theoretical amount of exhaust gas

$$g_t = a_t + \left(1 - \frac{a}{100} \right) = 14.4 \frac{kg}{kg} + \left(1 - \frac{0.0001}{100} \right) \approx 15.4 \frac{kg}{kg}$$

Actual amount of exhaust gas

$$g_a = g_t + a_e = 15.4 \frac{kg}{kg} + 21.6 \frac{kg}{kg} = 37 \frac{kg}{kg}$$

Mass flow rate of fuel

Average fuel consumption, 75 %, 1147 kW according to BISO Test protocol (Wärtsilä, 2003) = $199.65 \frac{g}{kWh} * \frac{1147kW}{1000} \approx 229 \frac{kg}{h}$

Average fuel consumption, 45 %, 700 kW = $150 \frac{kg}{h}$ (Stena Forecaster 2015, Movement book month of May)

Mass flow rate of exhaust gas

$$m_e = m_f * g_a$$

$$m_e \text{ 75 \%} = m_f * g_a = 229 \frac{kg \text{ fuel}}{\text{hour}} * 37 \frac{kg \text{ exhaust gas}}{kg \text{ fuel}} = 8473 \frac{kg}{\text{hour}}$$

$$m_e \text{ 45 \%} = m_f * g_a = 150 \frac{kg \text{ fuel}}{\text{hour}} * 37 \frac{kg \text{ exhaust gas}}{kg \text{ fuel}} = 5550 \frac{kg}{\text{hour}}$$

The result is compared with the W20 engine, from mail correspondence with Wärtsilä, and seems reasonable.

Steam demand

The steam output is calculated by the formula:

$$n_p = \frac{S * (h_s - h_{fw})}{F * H_i}$$

n_p = efficiency of boiler

S = steam output $\left(\frac{kg}{s}\right)$

h_s = enthalpy of steam output $\left(\frac{kJ}{kg}\right)$

h_{fw} = enthalpy of feed water to boiler $\left(\frac{kJ}{kg}\right)$

F = fuel consumption $\left(\frac{kg}{s}\right)$

H_i = fuel calorific value $\left(\frac{kJ}{kg}\right)$

The calculations are done in the following steps:

Fuel calorific value

$$H_i = 0.339 * c + 0.105 * c + 1.21 * \left(h - \frac{o}{8} \right) - 0.0251 * f = 42460 \frac{kJ}{kg}$$

“A fuel heating value is often determined by combustion in a so-called bomb calorimeter, obtaining the so-called calorific value H_s . The net calorific value (H_i) is obtained by subtracting the heat of vaporization from the calorific value.” (Andersson, 2013)

Efficiency of boiler, Aalborg Mission OS 3300

$$n_p = \frac{S * (h_s - h_{fw})}{F * H_i} = \frac{2800 \text{ kg/h} (2762 \frac{kJ}{kg} * 378 \frac{kJ}{kg})}{184 \frac{kg}{h} * 42200 \text{ kJ/kg}} = 0.8596 = 86 \%$$

Aalborg Mission OS 3300 Technical data

$$P_{steam} = 7 \text{ bar (Aalborg Industries, 2003)}$$

$$T_{steam} = 165 \text{ C (Aalborg Industries, 2003)}$$

$$P_{fw} = 17.5 \text{ bar (Aalborg Industries, 2003)}$$

$$T_{fw} = 90 \text{ C (Aalborg Industries, 2003)}$$

$$H_i = 42\,200 \frac{kJ}{kg} \text{ (Aalborg Industries, 2003)}$$

$$F = 184 \frac{kg}{h} \text{ Max burner capacity on diesel oil (Aalborg Industries, 2003)}$$

$$h_s = 2762 \frac{kJ}{kg} \text{ Specific enthalpy of saturated steam at 7 bars (Mollier diagram)}$$

$$h_{fw} = 378 \frac{kJ}{kg} \text{ Specific enthalpy of saturated water (Mollier diagram)}$$

The efficiency is compared with the boiler efficiency tested with Testo equipment on board the vessel to be sure of the high rate.

Efficiency tested with Testo equipment = **83.5 %**

Aalborg Mission OS 3300 Testo 330-1 results:

AT = Exhaust gas temperature

CO₂ = Carbon dioxide

qA = Exhaust gas losses

λ = Excess air

O₂ = Oxygen

CO = Carbon monoxide

out CO = Diluted carbon monoxide

NO = Nitrogen monoxide

NO_x = Nitrogen oxides

VT = Ambient temperature

n = Efficiency

DP = Dew point temperature of the exhaust gas

HFO	MGO
323.9 C	324.8 C AT
9.99 % CO ₂	10.05 % CO ₂
17.6 % qA	16.5 % qA
1.59 λ	1.53 λ
7.8 % O ₂	7.3 % O ₂
27 ppm CO	94 ppm CO
43 ppm outCO	144 ppm outCO
236.6 ppm NO	74.5 ppm NO
248.4 ppm NOx	78.2 ppm NOx
34.9 C VT	33.2 C VT
82.6 % n	83.5 % n
43.8 C DP	45.7 C DP

Table 2: Testo 330-1 Auxiliary boiler results



Figure 10: Testo 330-1 auxiliary boiler efficiency result

With this data the steam demand for the period could be determined.

Aalborg Mission OS 3300 case study:

$$P_{Steam} = 5 \text{ bar (Stena Forecaster, 2015)}$$

$$T_{Steam} = 152 \text{ C (Stena Forecaster, 2015)}$$

$$P_{fw} = 17.5 \text{ bar (Stena Forecaster, 2015)}$$

$$T_{fw} = 90 \text{ C (Stena Forecaster, 2015)}$$

$$F = 138 \frac{l}{h}, \text{ density} = 872.1 \frac{kg}{m^3}, 142 * 0.8721 = 120 \frac{kg}{h} \text{ (Stena Forecaster, 2015)}$$

$$H_i = 42\,460 \frac{kJ}{kg} \text{ VPS Specification report (Stena Forecaster, 2015)}$$

$$n_p = 0.835 \text{ (Stena Forecaster, 2015)}$$

$$h_s = 2748 \frac{kJ}{kg} \text{ Specific enthalpy of saturated steam at 5 bars (Mollier diagram)}$$

$$h_{fw} = 378 \frac{kJ}{kg} \text{ Specific enthalpy of saturated water (Mollier diagram)}$$

Steam demand, 04 May 2015 – 21 May 2015, Stena Forecaster

$$S = \frac{F * H_i * \eta}{h_s - h_{fw}} = \frac{120 \frac{kg}{h} * 42460 \frac{kJ}{kg} * 0.835}{2748 \frac{kJ}{kg} - 378 \frac{kJ}{kg}} = 1795 \text{ kg/hour}$$

To be taken with respect to the error. Steam output will differ widely depending of steam needs and weather conditions; this result represents an average for the period of 04 may 2015 – 24 may 2015

Payback time

Aalborg XS TC7A economizer steam output, load 75 %: ~400 kg/h (Alfa Laval, 2015).

Aalborg XS TC7A economizer steam output, load 45 %: ~300 kg/h (Alfa Laval, 2015).

The average required steam output on board Stena Forecaster during the period of 04 may – 21 may 2015 was 1796 kg/h. Knowing this the fuel oil savings in percent is as below:

$$\text{Fuel oil savings with 75\% load on the engine: } \frac{400 \frac{kg}{h}}{1795 \frac{kg}{h}} = 0.223 = 22.3 \%$$

$$\text{Fuel oil savings with 45\% load on the engine: } \frac{300 \frac{kg}{h}}{1795 \frac{kg}{h}} = 0.167 = 16.7 \%$$

In kg/hour the savings with an average fuel consumption of 138 l/hour will be:

$$\text{Average load, 75\%: } 138 \frac{l}{h} * 871 \frac{kg}{m^3} = 120 \frac{kg}{h} * 0.223 = 26.8 \frac{kg}{h}$$

$$\text{Average load, 45\%: } 138 \frac{l}{h} * 871 \frac{kg}{m^3} = 120 \frac{kg}{h} * 0.167 = 20.04 \frac{kg}{h}$$

Knowing the diesel oil price, the cost in euro is calculated in the following way.

$$\text{Diesel oil price as of 22 may 2015: } 583.5 \$ (\text{Ship\&Bunker, 2015}) = 531 \frac{EUR}{mt} \text{ (1 US Dollar = 0.91 EUR, 31 May 2015)}$$

This leads us to:

$$\frac{26.8 \frac{kg}{h}}{1000} = 0.0268 \frac{mt}{h} * 531 \text{ EUR} = 14.2 \frac{EUR}{h} \text{ savings}$$

$$\frac{20 \frac{kg}{h}}{1000} = 0.020 \frac{mt}{h} * 531 \text{ EUR} = 10.62 \frac{EUR}{h} \text{ savings}$$