EffShip

a project for sustainable shipping

WP4 ENERGY EFFICIENCY and HEAT RECOVERY

Report
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1 Introduction

1.1 Present situation

The EffShip project is based on the vision of a sustainable and successful maritime transport industry – one which is energy efficient and has minimal environmental impacts. Specific project goals to achieve this include improving the efficiency of the ship machinery, introducing alternative marine fuels, using wind energy as a complementary propulsion force and developing applicable technology for reducing the emissions of CO_2, NO_x SO_x and Particulate Matter. The project will result in solutions with respect to maritime fuels, energy efficiency and emission reduction technology that will contribute to the fulfillment of EU's and the Swedish Government's climate goals of 20% more efficient energy usage, 40% reduction of green house gas emissions, a minimum of 10% renewable energy in the transport sector in year 2020 and to fulfill and exceed upcoming international rules. In the project, there will be full scale tests of some of the developed technologies as well as a complete ship design including functional design of the best technologies. A state of the art ship design has been made available to the project to act as the platform for further development. The project results will be disseminated and exploited through the eight partners of the project consortium consisting of research organizations, ship design companies, suppliers of power and emission reduction solutions and heating systems.

1.2 Project Areas

The project addresses the area "Efficient energy use" for shipping, and also the area "Sustainable use of natural assets". The project is a combined Research, Technological development and Demonstration (RTD) project.

2 Summary –Energy Efficiency and Heat Recovery

2.1 Project Background

Conversion of fuel energy to mechanical energy is important for reducing costs of ship propulsion. State of the art is mainly technology where two stroke diesel engines running on cheap heavy fuel oil (HFO).

Having this as the outset we have analysed which technical and economical possibilities are at hand in the near future in order to improve and replace existing technologies which fulfil today´s demand on emissions and cost levels of the shipping industry.

2.2 Project Definition of Work Package 4

WP4. Energy Efficiency and Heat Recovery: The purpose of this WP4 is to identify and establish an overview of existing methods and techniques under development for improving energy efficiency(i.e. minimize the energy consumption) of the machinery, accommodation and outfitting systems and heat recovery of exhaust gas and cooling water energy. Areas for potential future development will be identified and ways to achieve this will be described.

2.3 Energy efficiency improvements

There are four areas for analysing how improvements could be made

2.3.1 Machinery

The machinery for propelling the vessel is the most energy consuming part where most gains can be obtained. The main engine has for many years been in focus to get the highest savings by improving the efficiency. There has been a continuous process already since the diesel engine started to be an efficient and reliable machinery for ship propulsion. The very first diesel engines had an efficiency of 35% and now the very best two stroke engines reaches well above 50%.

However, to calculate the specific fuel consumption or efficiency is a complex task and such rules can be found within ISO 3046, but it is also related engine load, engine speed, maintenance, vessel trim, and operational conditions of the crew. When the ship is delivered from the ship yard the engine performance are measured at the sea trial. This might be the only opportunity when the vessel's performance is accurately measured and calculated under calibrated and controlled conditions.

Ships are normally not equipped with on-line instruments to measure and to identify the optimal fuel consumption if such instruments could be found on the market. The energy content of bunker oil fluctuates and has to be checked in-situ when the vessel is taking bunker oil on-board. The sludge, after treatment in separators and filter, can constitute a great deal of the energy which cannot be used for propulsion.

2.3.2 Accommodation

The vessel accommodation includes space for crew and control rooms, storages. The power needed for keeping the accommodation comfortable varies substantially dependent of type. The power needed for lighting and HVAC (heating ventilation and air conditioning) is occasionally called house load.

In passenger vessel such as ferries and cruising vessel the house load constitutes a great deal of the power consumed in particular in tropical climate.

For tank/bulk with small crews the house load is relatively modest but may still effect the cost if MGO is used for the auxiliary engines for power generation

2.3.3 Outfitting

Outfitting encompasses equipment for cargo handling and auxiliaries outside the engine room e.g. pump rooms, mooring system.

The major consumers for ferries and roro vessel are the ventilation systems particularly at loading and unloading of the vessel. Even if the time at loading/unloading conditions is short in comparison of total operations the emissions will for the port constitute a substantial outlet of exhaust gases. Therefore land connection (cold ironing) is an attractive solution.

The power consumption of the cargo fans is a great load and for a vessel operation auxiliary engines on MGO a great deal of money can be saved if the fans operate as efficiently as possible. Frequently the fans operate at constant speed and if controlled the air flow is controlled by choking with the baffles.

3 Project Accomplishment

3.1

WP4 is a natural part of the total EffShip project why the results from the other work packages in particular WP2-Fuels, WP3-Emissions and WP5-Energy Transformers will be applied for various conclusions.

In order to get a grip of the opportunities and problems in existing vessels a measurement program was performed on Wagenborg roro-vessel M/S Spaarneborg.

3.2 Energy distribution

The Sankey-diagram is a very comprehensive way of identifying how energy is distributed in an engine with respect to temperatures. Temperature is a very fundament feature in thermodynamics for a scientific way of finding the optimal heat recovery routes.

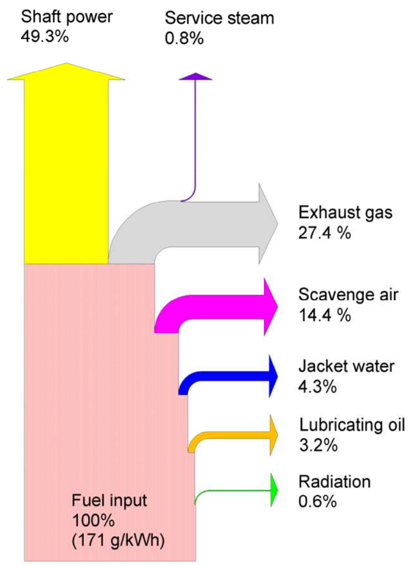

Figure 1 Sankey diagram of a two stroke diesel engine

The depicted Sankey diagram fig.1 is a good representation of the Spaarneborg main engine. If the standard fuel has a low heating value of 42.7 MJ/kg and the fuel consumption is 171 g/kWh at the shaft the corresponding engine efficiency is 49.3 % LHV. This figure has earlier been verified for Spaarneborg.

It can be seen that 27% of the residual heat is within the exhaust gas. The high temperature (jacket water and scavenging air) engine cooling water holds 19% and the low temperature (lubrication oil) engine cooling holds approximately 3%. Thus big amounts of low temperature energy are available and it is difficult find cost effective ways to utilize this energy.

In Spaarneborg an exhaust gas boiler is installed for steam generation. The steam is primarily used for heating HFO bunker oil and accommodation heating.

Some engine cooling is used in the evaporator for producing fresh water to the accommodation and boiler make-up.

3.2.1 Energy Efficiency

Energy efficiency is related to the on board consumers with respect to reducing the needed power obtaining the necessary operational conditions. Energy saving in the engine itself is not covered in Effship but externals method for minimizing the fuel consumption is covered in WP5-Energy Transformers.

The energy used on board is divided in machinery, accommodation and outfitting as describe in paragraph 2.

The onboard consumption varies depending on the operating conditions; at sea the consumption is mainly for propulsion and in harbour mainly handling equipment.

Big variations can also been seen in different climatic condition when operating in either arctic or tropical conditions.

3.2.2 Heat Recovery

Heat recovery from the exhaust gas system including boilers and engine cooling with heat exchangers has been in focus as great energy savings can be made not least if cleaner fuels can be used. Conversion of various fluids to steam/mechanical energy has been thoroughly studied.

The design point of the main engines has been analysed with respect to off design conditions in order to get improved performance during various operating conditions.

Low temperature heat from the engine cooling system can be recovered for generating chilling for the air condition system

The propeller characteristics are an essential part for efficient propulsion and is only to a limited extent covered.

3.3 Conclusions of obtained results

As a reference of a ship's performance a propulsion system with a direct driven fixed propeller of a two stroke HFO engine been chosen.

With today´s technology it is fully achievable to replace the reference technology with enhanced systems meeting both emission legislations and cost levels.

It is already demonstrated on big container vessels with heat recovery to obtain gross efficiencies of 53% when big engines are used operating regardless of emission restrictions.

As shown in this project the same figures can also be obtained on smaller vessel also meeting the more stringent emission demand.

However, new cleaner fuels such as methane (LNG) and alcohols (methanol) will be introduced in order to obtain improved heat recovery. The ship will install heat recovery components for bringing the energy down to the propeller shaft. Energy savings shall be introduced where thermal energy can replace mechanical e.g. air conditioning, and frequency converters shall be applied for running bigger pumps and fans.

Cleaner fuel implies less power or none for exhaust gas scrubbers and catalyst cleaning systems.

Thanks to heat recovery from exhaust gases and engine cooling the propulsion power could be improved by 10% which corresponds to an efficiency improvement of 4% units.

If a clean fuel e.g. LNG is used a 30% reduction of CO_2 is obtained. If clean fuel e.g. LNG and methanol are used additional heat can be recovered thanks to low fouling.

When refrigeration fluids are used at low temperature additional power can be recovered

By choosing a suitable propeller design a few more percent units can be saved.

Thus, this report complies various energy technologies and discusses how established and new technologies can be adapted the marine environment.

4 Energy efficiency

4.1 Auxiliary consumers

Auxiliary power consumers are for either supporting the propulsion of the vessels or for supplying power to handling equipment in harbour.

Pumps and fans are very common on-board and constitutes the major power consumers. Pumps are normally defined in volume flow e.g. m3/h and pressure rise as head in meter. As water density is 1000 kg/m3 it becomes easy to convert to flow rate in kg/s.

For calculating the power consumption of a pump some rules of thump could be applicable:

- Pump pressure in MPa (1 MPa=10 bar)
- Pump flow in kg/s
- Pump efficiency e.g. 70%
- Pump motor efficiency e.g. 80%

Example: A sea water pump has a pressure of 4 bar at a flow 50 kg/s the electric motor power will be 0,4*50/0,7/0,8=36 kWe.

4.1.1 Vessel at sea operation

For making the main engine operating safely and at low fuel consumption few systems should be in operations. Inherently some essential pumps such as engine cooling water pumps and lubricating pumps are mechanically direct driven by the engine. Such pumping is very efficient in itself as no conversion of electric power is needed. For safety reasons some back-up pumps will be installed but they are not in regular operation.

The pumps and fans in sea conditions can be divided in three categories; continuous operation, intermittent and stand-by.

Typical continuous operational pumps and fans are: Sea cooling pumps, fresh water cooling pumps, lubricating oil, engine room ventilation, separators, fuel booster pumps, evaporators

Intermittent consumers are: Compressors, transfer pumps

Stand-by pumps: Sea water, lubricating oil, fire pumps.

For saving energy it might not be viable to install speed control of very small pumps or systems which operates rarely but necessary for the vessel.

Many modularized systems are bought readymade and can be equipped with special energy saving facilities such as speed control or energy save control e.g. automatic switch off after some time.

Speed control

Much has been said over the year of speed controlled pumps and fans. The motor/pump-set is operating according to the pump curve which must fulfil pressure raise and flow characteristics over a wide operational span.

A conventional pump is designed for one single operating point which means the worse case with respect to flow and pressure, when the main engine runs at full load. Most engine load varies between 50-90% which makes the cooling system running off design. Despite this the pump is running at design point and controlled according to choking. Such a condition consumes a lot more power than necessary.

For the land based industry speed control is today the preferred standard and the capital cost is similar to the old direct driven system. However, the operating cost is substantially less. For ship's application a similar system can be applied as long as the safety arrangements meet the rules.

The likely pumps and fans to be equipped with speed control are sea water pump and engine room ventilation. For mechanically engine driven cooling water speed control is not applicable. When electrically driven lubricating oil pumps are installed speed control can be applied.

A proper designed sea water pump should be designed according to various operating conditions e.g. engine load variations, climatic conditions, draft conditions where pump and electric motor is a well common functioning unit with the control system containing not only frequency converter but also pressure and flow transducers.

	Design	Full load	Half load
Sea water	50	50	25
Fresh water	20	20	10
Lub oil	20	20	15
Ventilation	60	60	30
Fuel booster	18	18	18
Lighting	15	15	7
Total kWe	183	183	105

Table 1 Energy saving potential at speed control of some pumps

In table 1 are listed the major electrical consumers operating at sea necessary for a safe vessel operation. These consumers are continuously operating and designed according to given ships performance. However, when the vessel is operating off-design these consumers could be derated accordingly by introducing speed controlled pumps. Some other major consumers like lighting and ventilation should be control manually.

As seen almost half of the power consumption could be saved by modifying the major consumers.

If the vessel is operating 6000 hours at sea per year and the fuel is HFO at 700 $/ton the saving is around 50000 € per year.

4.2 Engine cooling heat recovery

The engine is cooled with fresh water in a closed loop whereas the fresh water is cooled in a central cooling water heat exchanger with sea water. Thus the engine waste energy is rejected to the sea. As seen from figure 1 Sankey diagram 23% of the primary energy is rejected to the sea.

It has been investigated if some of this energy could be recovered and replace some other power consumers.

4.2.1 HVAC

Heating ventilation and air conditioning (HVAC) is distributed within the vessel by air either heated or chilled.

Heating is arranged through heat exchangers where high temperature water is fed to the air ducting system. Similar is done for chilling the air in ducts having a cooling battery using a refrigerant as energy carrier, typically R134. By compressing the refrigerant cooling with fresh water and expansion in a valve a very efficient cooling can be obtained.

However the HVAC system is driven by electrically powered compressors. These compressors can be replaced with abortion chillers which can be driven by waste energy from the engine saving some electric power. Such a system has been considered in WP5- Energy transformer 7.2.6.

Vessels operating in colder climate need accommodation heating which could be quite extensive for ferries and cruisers. Today when ferries are at quay boilers are in operation keeping the accommodation at a comfortable temperature.

To avoid the boilers operating heat storage could be applied; charged during the sea voyage and discharged when the vessel is at quay. If a ferry requires 2 MW heat at quay and is moored for twelve hours it could be sufficient to have a heat storage of 400 m3 water charged with 95 °C and return water of 50 °C. The engines will then have a capacity to charge the storage with 25 MWh heat from the engine cooling circuit.

It is also possible to store the heat in a thermal oil tank which then of course requires a thermal oil boiler for heat recovery of the exhaust gas energy. Thermal oil has the advantage to store energy at a much higher temperature above 250 °C and a return water around 100 °C.

In table 2 a comparison between a hot water storage system and thermal oil storage system are shown. As seen the hot water tank is slightly bigger than the thermal oil tank.

	Hot water	Thermal oil	
Heat demand	2000	2000	kWth
Store temp	95	250	°C
Return temp	50	100	°C
cp	4,19	2,01	kJ/kg K
Density	1000	900	kg/m3
Tank size	389	311	m3
Flow	10,6	6,6	kg/s

Table 2 Data for Storage systems

The physical properties of thermal oil are different from water as the heat capacity increases with temperature while density is reduced. Thermal oil is of different qualities and varies from composition and manufacturer. Special well insulated tanks have to be installed and only heat from the exhaust gases can be utilized.

4.2.2 ORC

The abundance of engine cooling water is enough for also generating power from an organic rankine cycle (ORC). However, the outgoing temperature of the engine is around 85 °C which is a bit low. To fit better the cooling water temperature would be in the range of 95-98 °C. Such a temperature is most likely only achievable for a new building where the engine cooling system is designed with a split charge air cooling system.

If the engine cooling is used for an ORC the expected efficiency is 5-7%. Thus for a 10 MWe engine the ORC output would be around 200 kWe. If sat steam is available some more power could be obtained. For further ORC application see WP5.

4.3 Energy storage

It has always been a dream to store energy in particular for electricity generation. On land pumping power plants have been built by pumping excess power during night time to a water dam which during day time has been discharged.

However, for a vessel the problem is a lot more complex. If thermal oil (TO) heat storage is chosen there is an opportunity to store heated oil to be recovered.

From table 2 it can be seen that 2000 kW heat can be extracted when the tank is fully charged at a TO temperature of 250 °C. At this temperature we can assume a conversion efficiency of 8-10% giving a output of about 175 kWe. Cold TO is flowing back to the tank and will be mixed implying a lower feed temperature and a lower power output until the process stops and the tank has to charged again.

If the tank can store 24000 kWh heat let’s assume in average 7% can be converted to power giving a recovery of 1700 kWh electricity or 140 kWe for a twelve hours period.

If a vessel has a six hour turn around in harbour with shore connection the TO system can be used for heating cabins, hotels and giving power to the ship’s grid by using a TO driven ORC system of 200 kWe.

5 Spaarneborg data acquisition

5.1 Vessel engine particulates

The roro vessel is owned by the Dutch ship-owner in the Netherlands and operated by Swedish Orient Line and is basically transporting paper for Stora Enso the Finnish-Swedish paper manufacturer. She mostly operates in the Baltic Sea and via Gothenburg to Zeebrugge.

The vessel was built in 2000 and is equipped with a two stroke Sulzer 7RTA52U with a power of 10920 kW directly connected to CP propeller. There is also a deNOx system installed delivered by DEC Marine.

The exhaust gas system hold an exhaust gas boiler for generating saturated steam of 7 bar for bunker and hotel heating same some smaller consumers. A shaft generator is connected via a gear box to a frequency converter.

5.2 Vessel trips

In order to evaluate the prevailing operating conditions an S-man representative joined the crew to find out and measure actual performance during an ordinary sea voyages.

The measurements took place during two occasions; unfortunately the first one took place under very rough weather conditions and the results were not good enough for an accurate evaluation of the performance. The second voyage took place under pretty good conditions why the captain facilitated the measurements by letting the vessel operate under various speeds and conditions.

5.3 Measurements

The objective with the measurements was to find out how much steam could be generated at various loads and how steam was used at various consumers. The basic question was to find out if some excess was available for other consumers or if the boiler could be modified to generate some additional steam.

As the vessel was operated at various loads from 45-90% a rather good estimate could be done as seen from column 2-4 in table 3. The 100% load is extrapolated from measured results seen in fig 2.

1	1	2	3	4	5	3
2	Load	90%	62%	45%	100%	62%
3	O2	14,6%	15,4%	15,3%	14,5%	15,4%
4	Tin	268 C	255 C	277 C	270 C	255 C
5	Tout	231 C	218 C	238 C	232 C	218 C
6	Fuel	2040 kWth	1385 kWth	1050 kWth	2270 kWth	1385 kWth
7	Exhaust	25,2 kg/s	19,4 kg/s	14,5 kg/s	27,6 kg/s	19,4 kg/s
8	Steam 7 bar	1,77 ton/h	1,35 ton/h	1,07 ton/h	1,99 ton/h	1,37 ton/h
9	***kW***	***1195***	***915***	***722***	***1342***	***925***
Dump		***213***	***202***	***230***	***222***	
Used kW		***982***	***713***	***492***	***1120***	
Excess ton/h		0,32	0,30	0,34	0,33	
Used ton/h		1,45	1,05	0,73	1,66	

Table 3 Exhaust gas and steam measurement from voyage March 2011

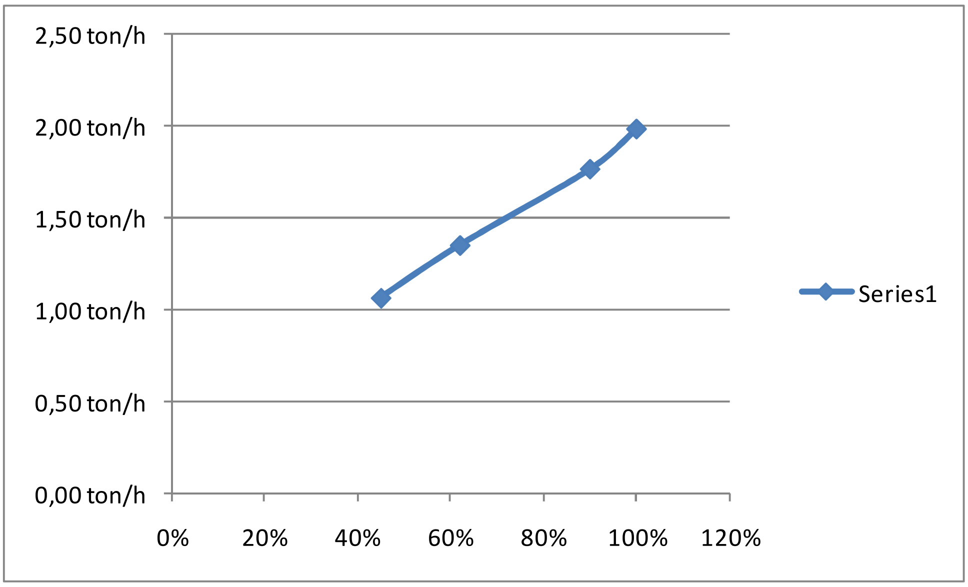

Figure 2 Steam generation capacities at 7 bar sat

It can be seen from fig 2 that the existing boiler can generate 2 ton/h sat steam when the engine is at full load. However, it is at very few occasions when the engines run full and during prevailing market conditions with slow steaming the engine is mostly operated at half load. Thus the steam generation is some 1 ton/h. During the sea trial the steam demand was occasionally high and the donkey boiler was started.

5.4 Exhaust gas boiler modification

The design criteria of the boiler should be a boiler providing sufficient steam for the consumers at MCR 90% without support of the donkey boiler. As the vessel nowadays operates below MCR the generated steam is not enough to heat the bunker and provide steam for the hotel why the donkey boiler has to be started and increase the fuel consumption using high cost MGO.

In fig 3 can be seen how the existing boiler performs at full load and maximum 2 ton/h can be generated. The exhaust gas temperature is high indicating that more heat could be generated if the size of the boiler was increase. Thus heat absorption could be increased if the surface area was extended.

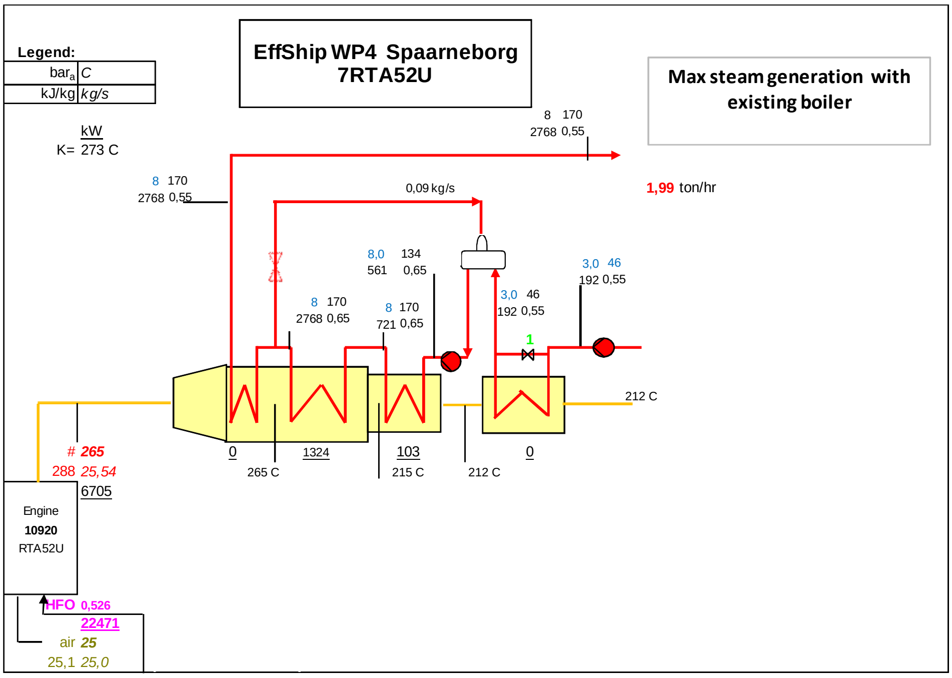

Figure 3 Prevailing performance of existing boiler

If sufficient space is available in the shaft there is an opportunity to add surface area. For avoiding sulphuric acid condensation the exhaust temperature shall not go below 180 C and if the return water is around 40 C around 3 ton/h could be generated, a steam capacity increase of 50%. So even when the vessel is slow steaming more steam could be generated and fewer operating hour of the donkey boiler with high cost fuel can be obtained.

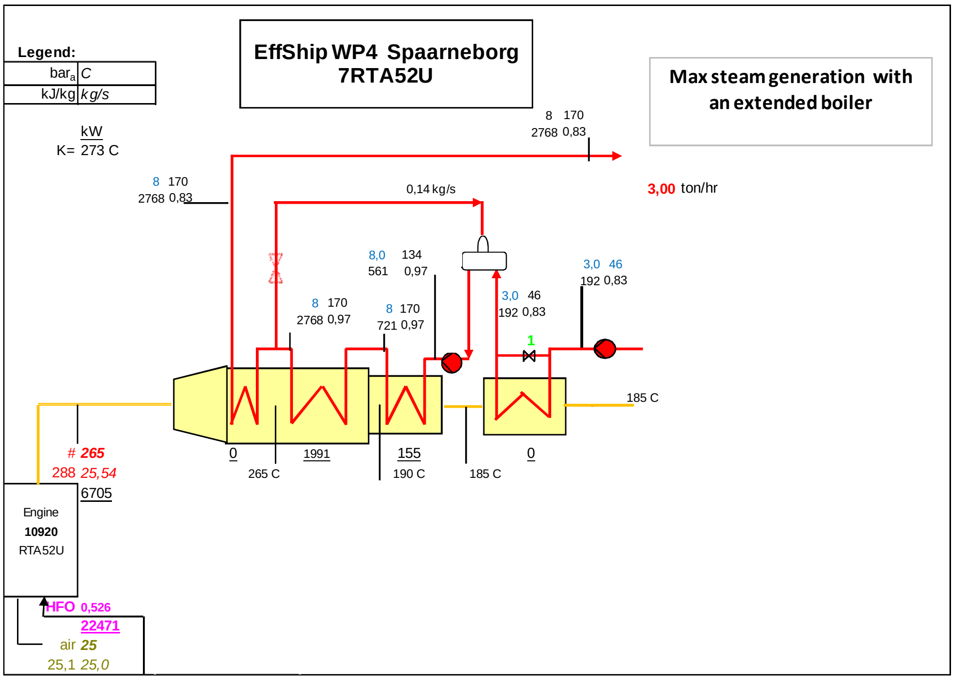

Figure 4 Capacity increase for a modified boiler

6 Engine capacity

The engine size of a vessel is beyond this study but constitutes an essential parameter for design of the bottom cycle.

Mostly only parts of the installed capacity. At multi engine installations only some of the engines are in operation or at part load when the speed demand is reduced and slow steaming is requested.

Part load is the most frequent operating condition to propel the vessel together and with operating time the energy availability can be estimated in MWh. The designed capacity in MW of the bottom cycle is based on actual part load. If not, the installation will be oversized with reduced viability.