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Review on Advances in Marine Diesel Engines and Its Impact on Ship Designs

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ABSTRACT

The aim of this paper is to take full advantage of the waste heat which is being dissipated into the surrounding atmosphere from a diesel engine in which 25.5% by the exhaust gases, 14.1% and 6.3% by air cooler and jacket water correspondingly. A waste heat recovery system is used to recover exhaust energy, waste heat from the coolant system, and released heat from turbocharged air in the intercooler of a diesel engine. By using waste heat from the engines, the efficiency of the combustion process can be significantly improved, manufacturers claim that savings in fuel consumption and fuel costs can be up to 10%.Waste Heat Recovery System is one of the foremost energy reduction system to make a more efficient usage of fuels to achieve environmental improvement as well as saving the amount of energy which is being wasted from the Main engine power. The recovered energy of 11.4% is converted into mechanical energy to run the electrical generator to meet the power demands onboard ship and some part of the energy is being utilized on the steam service system, which ultimately is going to impact the designs of the ship.

KEY WORDS: *Waste Heat, Waste Heat Recovery System, Efficiency.*

NOMENCLATURE

WHR	Waste Heat Recovery
PTG	Power Turbine and Generator
STG	Steam Turbine and Generator
$MARC$	Modular Arrangement Concept
MMT	Maersk Maritime Technology

1.0 INTRODUCTION

Today the greater part of the Prime Movers (Propulsion arrangement) and auxiliary plants of sea going vessels are Diesel Engines. High Pressure combustion engines are still the basic propeller for the ships due to the highest efficiency as compared to the other Diesel engines. Whilst enrouting, Diesel engines onboard have an efficiency of about 60% and the remaining amount of energy is being dissipated into the surrounding atmosphere in terms of exhaust gas and jacket water [1].However, a lot of work is being carried out and is in the development towards a better refinement of the thermal efficiency by enhancing the layout of the engine to achieve a better fuel consumption. A high end substitute approach in surpassing the overall energy efficiency is to reproduce and retrieving the 'Waste Heat'.

Waste Heat Recovery System is one of the foremost energy reduction systems to make a more efficient usage of fuels to achieve environmental improvement as well as saving the amount of energy which is being wasted from the Main engine power. It enables ship-owners to make better use of existing energy within the vessel’s full combustion cycle. By using waste heat from the engines, the efficiency of the combustion process can be significantly improved, manufacturers claim that savings in fuel consumption and fuel costs can be up to 10%.It is easier to make use of the firm waste heat on the ships as compared to that of the automobile. Furthermore, it can provide both heat source (waste heat) and cooling source (sea water).

The world's merchant fleet represents almost 80% of all the vessels ordered each year. Among them 85% will be having two stroke engines for propulsion with the remaining having four stroke engines. The energy regaining from the engines is relying up to a greater degree on the main engine load and ambient temperatures. Scappin assessed the performance of a two stoke diesel engine by means of an energy balance. He investigated the energy balance and used combined cycles to reclaim energy from other waste heat sources [2].

Therefore, to apprehend and reuse the waste heat onboard is an emission free process for the costly fuel which is purchased and then being used for the propulsion system. Waste heat recovery cannot be used only as an environmental control measure but also for the boosting the efficiency of fuel consumption.

A lot of number solutions have been proposed to generate power, electricity and heating from the waste heat sources. As the flow rate of waste heat source onboard ships is in a considerable large amount, so the potential for waste heat recovery is particularly promising.

2.0 WASTE HEAT RECOVERY SYSTEM WORKING

2.1 Analysis of Energy Balance

Prior to research on recovering waste heat from the diesel engine, the analysis of the energy balance should be carried out to find out the possibilities of waste heat recovery. A study carried out on a two stroke diesel engine of MAN B and W Diesel with an approximation that 25.5% of the released energy is wasted from the exhaust as shown in Figure.1 at ISO ambient reference conditions at 100SMCR, and 16.5% and 5.2% is wasted from the air cooler and jacket water respectively. Assuming the average operation in service at 85SMCR is 58.344KW in 280 days a year, 24 hours per day, 31,726 tonnes of heavy fuel will be lost through the exhaust gas, air cooler and jacket water. Figure.1 shows that for the engine with the combination of WHRS the total efficiency will increase to about 55%.

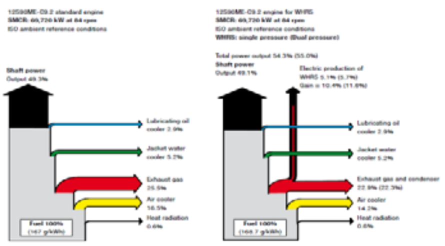

Figure 1: Heat Balance Diagram of a nominally rated 12S98ME-C9.2 engine.

Another study carried out by an another engine manufacturer Wartsila on a two stroke diesel engine has discovered that around 25.4% of the energy is being wasted from the exhaust and 12.9% and 6.2% is from the air cooler and jacket water appropriately. The possibilities are illustrated for Wartsila 12RT-flex96C engines as shown in Figure.2 with and without the waste heat recovery system showing in this case a 54.9% gain in overall efficiency with the waste heat recovery system.

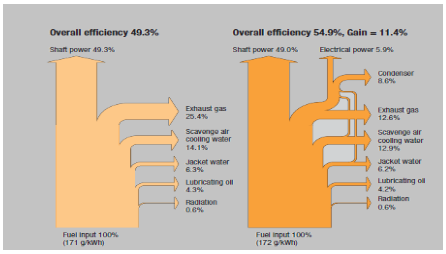

Figure 2: Heat Balance Diagram of a nominally rated 12RT-flex96C engine.

2.2 Working Principle

Modern marine engines such as the super long-stroke MAN B&W S90ME-C9 type or the Wartsila RT-flex series, uses the energy from the exhaust gases to increase the power that the engine can produce. In a typical arrangement, the gases leaving the engine are passed through a turbocharger, which uses the energy of the gas to spin a turbine that forms part of an air compressor. This compressor increases the mass of air that flows into the engine, enabling large quantities of fuel to be burnt more efficiently.

However, the energy of the exhaust gas can be used in other ways. First, it can be used to spin a power turbine that produces electricity. Secondly, it can be used to generate steam which can then be used in a gas-fired boiler to meet onboard heat demands. Systems that achieve either or both of the above are labeled as Waste Heat Recovery systems. Waste Heat Recovery systems are typically located in the main engine room.

As per[6] MAN B and W the principle of the Waste heat recovery system for the low speed diesel engine is that part of the exhaust gas flow is bypassed the main engine turbochargers through an exhaust gas bypass. As a result, the total amount of intake air and exhaust gas is reduced. The reduction of the intake air amount and the exhaust gas amount results in an increased exhaust gas temperature after the main engine turbochargers and exhaust gas bypass. This means an increase in the maximum obtainable steam production power for the exhaust gas fired boiler that is the steam, which can be used in a steam turbine for electricity production. Also, the revised pressure drop in the exhaust gas bypass, which is part of the WHRS, can be utilized to produce electricity by applying a power turbine. The main WHRS principles are shown in Figure. 3. As mentioned before, a WHRS consist of different components, and may wary as a stand-alone installation or a combined installation.

Choosing a system for a project depends on the power demand on board the ship (electrical load at sea), the ship's running profile (hours at different main engine loads at sea). A very important part of selecting the best WHRS for a ship project is choosing the best suited propulsion power and rpm for the ship, biggest possible propeller, so as to ensure the lowest possible fuel consumption for the basic performance of the ship.

In many cases, WHRS will be able to supply the total electricity need of the ship as a standalone power source, but it can also run in parallel with a shaft generator, shaft motor and auxiliary diesel generating sets. This type of advanced power system requires an advanced power management system.

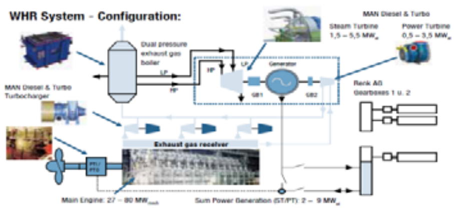

Figure 3: Waste Heat Recovery System Principle

3.0 WASTE HEAT RECOVERY INSTALLATION OPTIONS

Today several different WHRS are readily available. Depending on the level of complexity acceptable to the owner and shipyard and the actual electrical power consumption onboard, it is possible to choose between the following systems:

- ST-PT: Steam Turbine-Power Turbine generator. Power turbine and steam turbine generator with single or dual pressure steam turbine.
- STG: Steam Turbine Generator unit (Stand-alone, single or Dual steam pressure).
- PTG: Power Turbine Generator Power turbine stand-alone generator.

3.1 Power Turbine and Generator (PTG)

The simplest and cheapest system consists of an exhaust gas turbine (also called a power turbine) installed in the exhaust gas bypass, and a generator that converts power from the power turbine to electricity onboard the ship as shown in Figure. 4.

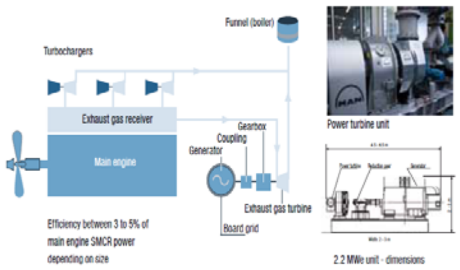

Figure 4: Schematic Diagram of the TCS-PTG System

The power turbine is driven by part of the exhaust gas flow which bypasses the turbochargers. The power turbine produces extra output power for electric power production, which depends on the bypassed exhaust gas flow amount. The TCS-PTG WHRS solution offers both standalone and parallel running electric power sourcing for the ship.

The exhaust gas bypass valve will be closed at an engine power lower than about 50% SMCR, where the engine will run with the same high efficiency as for a normal MAN B and W low speed two strokes engine.

3.2 Steam Turbine Generator (STG)

The second system builds on the principle exhaust gas by pass and, thereby, increasing the exhaust gas temperature before the boiler without using a power turbine. When applying the steam turbine (ST) as a stand-alone solution, the exhaust gas bypass stream is mixed with the exhaust outlet from the turbocharger(s), increasing the exhaust gas temperature before the boiler inlet.

When part of the exhaust gas flow is by passed the turbocharger, the total amount of air and gas will be reduced, and the exhaust gas temperature after the turbo charger and bypass will increase. This will increase the obtained able steam production power for the exhaust gas fired boiler. By installing a steam turbine (often called a turbo generator), the obtained able steam production from the exhaust boiler system can be used for electric power production. The steam turbine is installed on a common bedplate with the generator in the same manner as the power turbine and the generator.

Like the TCS-PTG design, the STG solution can function both as a standalone and as a parallel running electric power source for the ship, depending on the actual demand for the particular ship design. Using a WHRS STG system, it will be possible to recover some 5 to 8%, depending on the main engine size, engine rating, and ambient conditions.

3.3 Steam Turbine, Power Turbine and Generator

If the electric power demand on the ship is very high, e.g. a container ship, the power turbine and the steam turbine can be built together to form a combined system. The power turbine and the steam turbine is built onto a common bedplate and, via reduction gearboxes, connected to a common generator as shown in Figure.5.

MARC stands for Modular Arrangement Concept and is used both for power plants and for marine WHRS applications, and is the latest development of a steam turbine and power concept started in 1905 in Hamburg Germany.

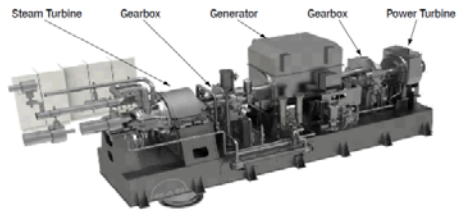

Figure 5: ST- PT System.

The power output from the power turbine can be added to the generator via a reduction gear with a special clutch. However, first the steam turbine will start at 30 - 35% SMCR main engine power followed by the power turbine which starts power production at 40 to 50% SMCR.

The combined WHRS ST & PT schematic diagram can be seen in Fig. 4, which shows a system that, in many conditions, reduces the fuel costs of the ship considerably by being able to cover the total electric power needs in many conditions onboard the ship. Otherwise, a shaft motor / generator (PTI/PTO) connected to the main engine shaft could be an option as shown in Figure. 6, making it possible to add either electric power to the ship grid if needed, or to boost propulsion by supplying the electric power to the PTI.

Selecting the full WHRS, combining both steam and power turbines, some8-11% power can be recovered, depending on the main engine size, engine rating and ambient conditions.

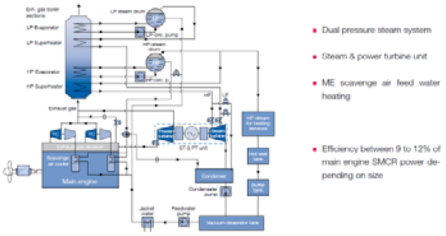

Figure 6: Schematic Diagram for the WHRS ST-PT System

4.0 CASE STUDY

4.1 Maersk

Maersk Maritime Technology has been an early pioneer with use of waste heat recovery technology. Maersk Maritime Technology (MMT) has previously stated that high fuel efficiency can be expected from installing waste heat recovery technology, compared to other systems, onboard vessels.

According to the company, currently 32 Maersk container ships in total have been fitted with the technology since the 1980s, achieving reductions in fuel costs of 9%. Since 2008, WHR has been installed on all containerships that have been ordered and will be on the ten new Triple E ships currently under construction. The first installation of the high efficiency WHR plant entered service in the 7500 TEU container ship Gurdun Maersk in June 2005. It successfully confirmed the benefits of the new WHR plant concept. During sea trials and in operation, the performance of the WHR plant exceeded expectations.

The ships are each propelled by a Wartsila 12RT Flex 96C low speed common rail engine with a maximum continuous power output of 68,640KW at 102rpm. Exhaust gases pass through dual pressure exhaust gas economizer from the Aalborg Industries to generate superheated steam which is utilized in a 6MWe turbo generator set. The turbo generator sets incorporate both a multi stage dual pressure steam turbine and an exhaust gas power turbine as shown in Figure.7. The generated electricity is supplied to the ship's main switch board and employed both in shaft motor/generator to assist in ship propulsion, and in shipboard services. A portion of the steam is used in the ship board heating services. The vessels are also equipped with the 3 diesel generating sets. The high efficiency WHR plants enables the ship to be fitted with one fewer diesel generating set than it would otherwise have.

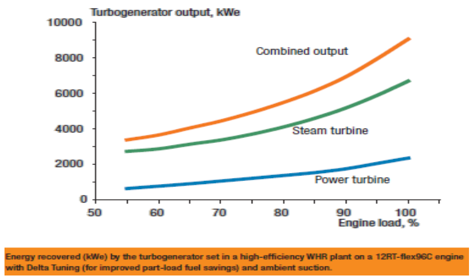

Figure 7: Energy recovered by a turbo generator.

The high efficiency WHR concept has been taken up further in the new 11,000 TEU container ships. The first class of this vessel is the Emma Maersk. She has been since then joined by number of sister ships. The ships are each powered by a 14 cylinder Wartsila RT Flex 96C common rail engine with an MCR power of 80,080 KW each at 102 rpm. This propulsion power is augmented by two shaft motors in each vessel. The main engines are each associated with a high efficiency WHR plant incorporating a turbo generator set having nominal output of 8.5MWe. as shown in Figure.8 This operates in conjunction with each ship's five diesel generating sets that have a combined output of 20.7MWe.

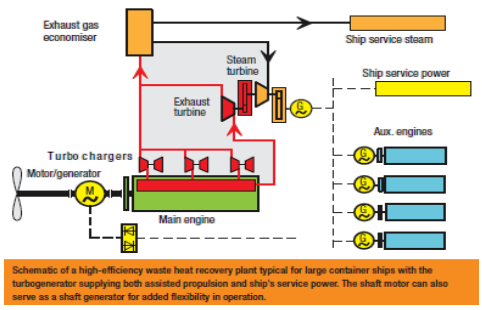

Figure 8: Waste Heat Recovery system for a large containership

4.2 Alfa Laval

As another sign of the growing uptake of this technology, Alfa Laval recently announced a waste heat recovery system that applies to auxiliary engines rather than main propulsion engines. The waste heat from the auxiliary engines has not been considered in the past, nevertheless it contains a large amount of energy that can be used to supplement ship steam requirements during voyage and especially during port stays.

Alfa Laval announced the Aalborg XS-TC7A technology in December 2012 following two years of sea trials. Alfa Laval announced the Aalborg XS-TC7A technology Fig.9in December 2012 following two years of sea trials [9].

It optimizes the use of heat energy from the auxiliary engine exhaust gases during voyage and port stays. When used in combination with a waste heat recovery system installed after the main engine, the Aalborg XS-TC7A contributes to significant reductions in the oil consumption on the oil-fired boiler under most load conditions.

Unlike the continual operation of the main engine during oceangoing voyages, the operation of the auxiliary engines varies. The Aalborg XS-TC7A, therefore, has been developed as a customized solution focused on generating energy under varying load conditions. To ensure the most advantageous design, the Aalborg XS-TC7A will be specially tailored to the individual ship and engine design with due consideration to the existing uptake back pressure and other critical factors.

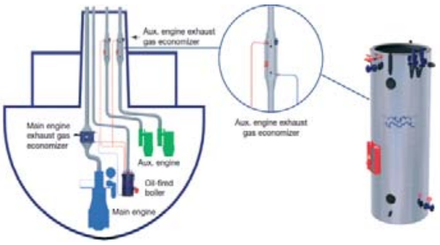

Figure 9: Aalborg XS - TC7A WHR System.

The economizer features an optimized and specialized convection part, which augments heat transfer caused by increased turbulence at the exhaust gas boundary layer. This provides the capability to increase steam production while reducing the weight and maintenance cost of the Aalborg XS-TC7A compared to other WHR systems.

5.0 ECONOMICAL BENEFIT

The economic benefits of the high efficiency waste heat recovery system can be illustrated as shown in figure. 10, by a case of a container ship powered by 12 cylinder Wartsila RT-Flex96C engine. In the case, the engine would operate at an average of 85% load for about 6500 hours a year on bunkers costing US$ 250/tonne, with an average total electrical load of 5350KW,including refer containers. The annual operating costs for the main and auxiliary engines, including fuel, maintenance and lubricating oil, would be US$ 19.54 million without a waste heat recovery plant and US$ 17.29 million with a high efficiency waste heat recovery plant.

HIGH-EFFICIENCY WHR: CASE STUDY

Basis ship:	
Main engine:	Wärtsilä 12RT-flex96C
CMCR power, kW:	80,080
Annual operating hours:	6500
Average engine load, %:	85
Total electrical load, kW:	5350
Auxiliary engines, kWe:	4 x 3000
Bunker fuel price, US$/tonne:	250
Cylinder lubricating oil price, US$/tonne:	1500

Annual engine operating costs	basis ship	with WHR
Fuel costs, US$:	18,449,000	16,359,000
Maintenance costs, US$:	486,000	333,000
Lubricating oil costs, US$:	602,000	559,000
Total, US$:	19,537,000	17,287,000
Annual savings, US$ at US$ 250/tonne fuel:	—	2,250,000
at US$ 400/tonne fuel:	—	3,482,000
Investment cost, US$	—	9,500,000

PAYBACK TIME LESS THAN 5 YEARS

Figure 10: Economical Benefit of a WHR Plant.

There would thus be annual savings of US$ 2.25 million. If the bunker price increased from US$ 250 to US$ 400/tonne, then the annual savings would increase to about 3.48 million. The complete high efficiency waste heat recovery plant and its installation would call for an investment cost of about US$ 9.5 million. This would thus have an expected payback time of less than five years.

6.0 NEW WASTE HEAT RECOVERY ON HORIZON

An innovative new waste heat recovery system is also set to enter the marine market. GE Marine announced a new licensing agreement with Echogen Power Systems LLC that will see the Echogen system sold to commercial and military marine vessels worldwide.

The Echogen system is different to traditional systems due to its use of supercritical carbon dioxide (CO_2), heated CO_2 that has properties of both a liquid and a gas, as its working fluid, rather than steam. This is said to make the system more compact and economical than a traditional waste heat recovery system.

As per Echogen Fig. 11, the CO_2 heat engine will mainly be comprising of five main components, namely exhaust and recuperator heat exchangers, condenser, system pump and power turbine. Auxiliary components involve valves and sensors which provides the system monitoring and control. Heat energy is introduced into the sCO_2 power cycle by the exhaust heat exchanger being mounted into the exhaust stack from a diesel engine. The available technology converts energy that traditionally gets exhausted out of a stack into useful power allows the overall system efficiency to increase by up to 30%. The product can operate efficiently in a broad range of exhaust temperatures, and the working fluid can be expanded for cooling or a combination of power and cooling.

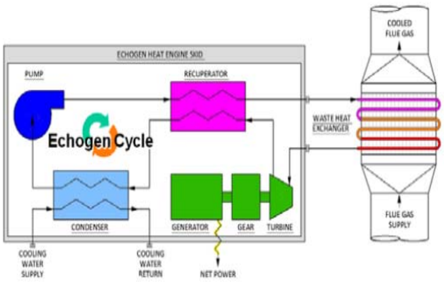

Figure 11: Supercritical CO_2 Power Cycle.

7.0 CONCLUSION

The overall concept of this paper is to provide ways of recovering waste heat from the exhaust gases of the diesel engine. The engine manufacturer Wartsila states that their high-efficiency WHR system which uses both power and steam turbines could cut exhaust emissions and deliver fuel savings of up to 12%, with a return on investment of less than 5 years. The engine manufacturer MAN Diesel and Turbo is more conservative in their claims. They suggest energy savings of 4-11% for their WHR systems, depending on a range of factors such as the operational profile of the ship, electricity demand whilst at sea, and the power level of the engine.

It must be remembered that the modern age, low speed engines are very highly developed and there is little potential for achieving significant savings in fuel consumption, and thereby reducing CO_2 by engine developments alone. Yet major improvements can be gained by using proven technology and hardware through applying the high efficiency waste heat recovery plant.

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