

REVIEW OF ORGANIC RANKINE CYCLE HEAT RECOVERY TECHNOLOGIES APPLICATION FOR MARINE DIESEL ENGINES

Tomas Čepaitis¹, Sergejus Lebedevas²

Department of Marine Engineering, Faculty of Marine Technologies and Natural Sciences, Klaipėda University

El. p. ¹tomas.cep7@gmail.com; ²sergejus.lebedevas@ku.lt

Abstract. CO₂ emissions from international shipping could increase between 50–250% by 2050 year. The EEDI (Energy Efficiency Design Index) is a key requirement for regulating CO₂ emissions of maritime transport; a requirement was introduced in 2011 by the International Maritime Organization and came into force gradually. In recent studies it was investigated that no other technologies have the potential and reserves compared to Cogeneration systems. The article provides a short review of ship energy efficiency design index improving technologies and cogeneration systems application for maritime transport which have direct relation with CO₂ emissions. A brief comparative analysis of cogeneration cycles is provided also.

Keywords: EEDI, waste heat, cogeneration, energy efficiency, decarbonization.

Introduction

Greenhouse gases (GHG) are becoming more and more increasingly dangerous to the global climate. In 2015, the 2030 Agenda for Sustainable Development and its 17 Sustainable Development Goals (SDGs) were adopted by all UN member 193 countries because greenhouse gas emissions are getting at their highest levels in history (International Maritime Organization, 2014b; Intergovernmental Panel on Climate Change, 2014; International Maritime Organization, 1997). A significant part of these emissions takes the transport sector which contributed 29% of global CO₂ in 2016 as almost all transportation energy is provided by petroleum-based fuels, gasoline and diesel. International shipping takes part of approximately 11% of transport sector emissions and it is expected to increase in the future as about 90% of world trade is carried by sea (International Maritime Organization, 2016, 2014b; International Chamber of Shipping, 2015; European Commission, 2014). Generally shipping is the most environmentally friendly in the transport sector in terms of CO₂ produced per metric ton of freight and per km of transportation (World Shipping Council, 2009). However, the fact that maritime transport is getting more and more energy efficient, shipping is still a big factor of

global greenhouse gas (GHG) emissions which contributes around 940 million tons of CO₂ annually. The IMO third greenhouse gas emission study envisions that even with predicted increase in ship average efficiency of 40% and without any further regulations, CO₂ emissions from international shipping could increase between 50–250% by 2050 (International Maritime Organization, 2014b). The aim of this publication is to review CO₂ emission reduction technologies of maritime transport, introduce heat recovery systems with cogeneration cycles and compare their practical application based on recent studies.

Potential technical solutions

At 2011 July, Marine Environment Protection Committee introduced Energy Efficiency Design Index (EEDI) requirement which was implemented in 2013 January 1st and will be stringent by three phases every 5 years starting from 2015 (Transport & Environment, 2017). This requirement implementation estimates of potentially reduce CO₂ emissions from 10% to 50% per transport work. Basically EEDI requirement regulates CO₂ reduction level for the majority new ship types depending on their size. Complex EEDI calculation formula if simplified in words consists of engines parameters and innova-

tive technologies expressed in grams of CO₂ per ships capacity-mile. In short terms, improving ship's EEDI, CO₂ emissions are reduced (International Maritime Organization, 2014a, Annex 5, Resolution MEPC.245(66); Devanney, 2010). These regulation factors made ship owners to meet the requirements and approach reducing fuel consumption. There are multiple solutions for fuel saving divided to operational measures (voyage execution, engine monitoring reduction of auxiliary power, weather routing, hull/propeller polishing, trim/draft optimization, slow steaming and etc.) and design measures (more efficient engines, propellers, hull design improvements, wind propulsion). Also, there are innovative technologies as wind and solar power utilization which are not commonly used due to limitations of specific ship type, space deficiency and inconsistent conditions (Nyanaya & Vu, 2019; Quoilin et al., 2013).

Energy efficiency guidance was published from class societies and industrial manufacturers. In example, DNV GL included these measures for energy efficiency improvements:

- Hull form optimization;
- Propulsion efficiency devices;
- New materials (lighter weight);
- Anti-fouling and coating of the hull to prevent drag increasing over time;
- Waste heat recovery;
- Auxiliary engine economizer;
- Main engine tuning;
- Electrification of the ship and switching to DC grid;
- Speed optimization.

The most common way in 2014 was slow steaming, cleaning hub and propeller (Tezdogan et al., 2015) but it led to longer payback period of investments costs. Recent several studies, reports and papers conclude that none of mentioned measures could have effective potential to the utilization of waste heat recovery systems as the main energy (approximately 50%) is wasted through exhaust gases and cooling when no heat utilization system is used (International Maritime Organization, 2011; Det Norske Veritas, 2012, 2015; Bombarda et al., 2010; Ančić et al., 2014; Ančić & Šestan, 2015; El Geneidy et al., 2017; Ito & Akagi, 1986; Schmid, 2004). Great fuel saving opportunities in ships is hidden in the utilization of the exhaust gas heat of internal combustion engines and gas turbine units. Exhaust gas temperatures of various type marine engines are between 260–450 °C. This makes it possible

to receive such amount of steam in utilization steam boilers that it would be possible to use it to increase energy efficiency up to 10% and to provide household consumer needs of heat and electricity as a pair (Mollenhauer & Tschöke, 2010; Hon & Wang, 2011).

Waste heat recovery systems

WHRS and innovation technologies were described as one of the most efficient ways of energy efficiency improvement in the machinery department as it can be used in parallel with other technologies as hull and propulsion optimization and reduce emission up to 14% (Wärtsilä, 2009; Guangrong, 2017; Bouman et al., 2017; Gilbert et al., 2015; Lindstad & Eskeland, 2015; Rehmatulla et al., 2017; Larsen et al., 2014a; Mansoury et al., 2018).

Modern diesel engines have up to 50% efficiency of total fuel energy supplied and other 50% is lost to surrounding as heat losses (MAN Diesel & Turbo, 2008). All this energy is lost through exhaust gases, cooling circuit, lubrication circuit, radiation due this fact efficiency waste heat recovery systems (WHRS) were implemented to save fuel. This waste heat is unused energy resource and WHRS can utilize the big part of remaining wasted heat for producing electrical and mechanical useful power that can be used additionally for propulsion and auxiliary need without additional fuel (MAN Diesel & Turbo, 2009). Well known marine machinery manufacturers offer multiple waste heat recovery systems (WHRS) and are available commercially (Wärtsilä, MAN, Dresser Rand, MHI-Mitsubishi Heavy Industries, Siemens). They can be equipped with a steam turbine (powered by the exhaust gas boilers) and/or a gas turbine (fuelled bypassing a part of the exhaust gas from the turbochargers of the main diesel engines) for electric or mechanical surplus power generation (Schmid et al., 2004). For example, MAN B&W Diesel turbo offers several WHRS, it is possible to choose between following systems by MAN (MAN Diesel & Turbo, 2014):

- ST-PT – Steam Turbine-Power Turbine generator unit (Power turbine, steam turbine, gear and generator unit with single or dual pressure steam turbine);
- STG – Steam Turbine Generator unit (Steam turbine, gear and generator unit, single or Dual steam pressure);
- PTG – Power Turbine Generator unit (Power turbine, gear and generator unit).

Part of the exhaust gas flow is by-passed the main engine turbocharger through 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 turbocharger(s) and exhaust gas bypass. This means an increase in the maximum obtainable steam production power for the exhaust gas fired boiler – steam, which can be used in a steam turbine for electricity production, but steam amount for domestic use decreases. Also, the revised pressure drop in the exhaust gas bypass, which is part of the WHRS, can be utilised to produce electricity by applying a power turbine (MAN Diesel & Turbo, 2014). The main WHRS principles are shown in Figure 1. Working fluid is heated in the exhaust gas boiler; working fluid (steam) expands in the turbine where which provides power. MAN Energy solutions states recovery rate up to 12% of the main engine power can be achieved and fuel reduction of 4–11% is possible.

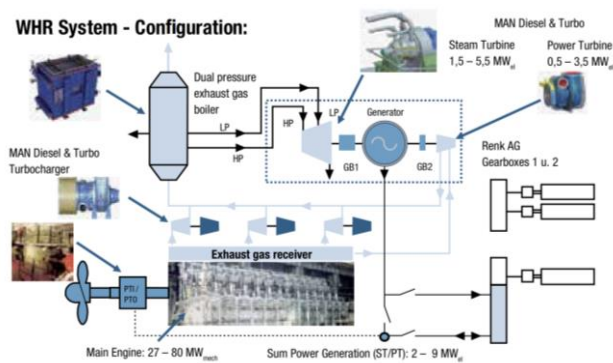


Figure 1. MAN B&W Waste heat recovery system principles

Another well-known marine machinery manufacturer “Wartsila” system called the Marine Engine Combined Cycle’ (ECC) is based on Organic Rankine Cycle (ORC), which recovers exhaust gas and jacket water waste heat, was developed by Turboden and Wartsila cooperation, and it was asserted that system would increase the main engine power from 8% to 12% and save up to 17% of total energy (Yadav et al., 2010). The integration of ECC into ship main engine is shown in Figure 2. Working fluid is heated by the exhaust gas from the main engine in the boiler; fluid evaporates and expands in the turbine where power is created through generator. Further fluid is condensed and goes to the pump and the cycle repeats.

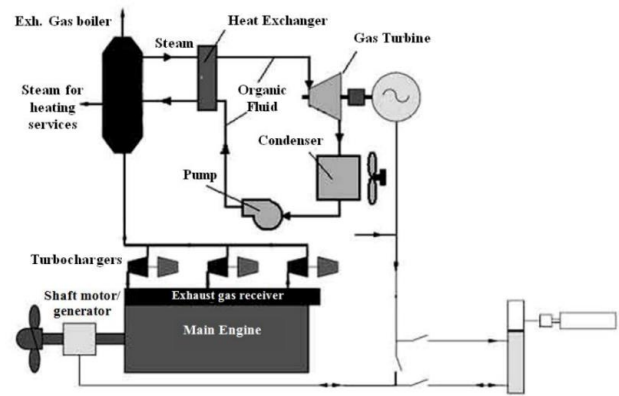


Figure 2. Wartsila & Turboden developed ECC system integration with ship engine

Wartsila plants are designed to run on a wide range of liquid, gaseous fuels and bio fuels while securing low emissions and high efficiency.

Cogeneration cycles

Comparative analysis of a commonly used cogeneration cycles are reviewed for maritime application (Noor et al., 2015). There are several ways to recover waste heat energy produced by diesel engine on board of ships, most widely used effective cogeneration cycles are Brayton, Kalina, Rankine.

The Brayton cycle is a constant-pressure cycle typical of gas turbine (GT) engines to produce mechanical power (basis of the jet engine and others). Brayton cycle consists of a heat exchanger to recover the exhaust heat, a turbocharger system to compress air and convert the heat energy into mechanical work and an electric generator integrated into the turbocharger shaft to generate electric power (Liu et al., 2016). Basic Brayton closed cycle scheme is presented in Figure 3. The working fluid is compressed in the compressor and further it enters recuperator where heat content of the turbine exhaust is regenerated. After regeneration working fluid goes through the heat source where achieves the highest temperature in the cycle expansion in the turbine is performed which provides power for compressor and generator. Exhaust from turbine is used to preheat working fluid in recuperator after that heat is eliminated and working fluid cooled to primary conditions (Olumayegun, 2017; Deng et al., 2017). Gas turbine are often used in Navy ship due to the compact size and part load operating mode but are complex in maintenance and high price, therefore it is not commonly used in international shipping (Kuo & Shu,

1979; Budiyanto & Nawara, 2020). Sharma et al. researched WHRS using Brayton supercritical carbon dioxide regenerative recompression cycle and the results showed that overall efficiency of the system improved by 10% (Sharma et al., 2017).

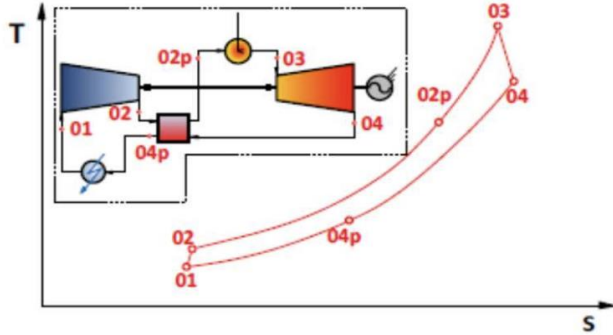


Figure 3. Brayton closed cycle gas turbine

The Kalina cycle is a new concept in heat recovery and power generation, which uses a mixture of 70% ammonia-30% water (proposed by Dr. Alexander Kalina in 1983). It is modified form Rankine cycle. In Figure 4 Kalina cycle with reheat process is shown.

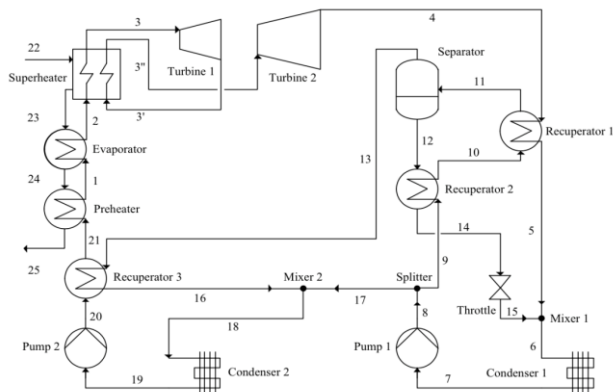


Figure 4. Kalina cycle process

“The pre-heated working fluid (1) is evaporated and superheated in the boiler and then enters the turbine (3). Outlet Stream from turbine is heated in the boiler 3” and it enters the second turbine. From the second turbine working fluid stream enters recuperator where the heat is transferred to another stream 10. Afterwards, recuperator stream (5) is mixed with an ammonia lean stream from the separator (15) to form a leaner solution. This solution is condensed (7) and after being pumped to an intermediate pressure level, the stream (8) is divided in two streams (9) and (17). The stream (9) is heated in Recuperator

(2) and in recuperator (1) to partially evaporated state. It then enters the separator which separates the stream into lean liquid (12) and very rich vapour (13). Heat from stream (13) is used to preheat stream (20) in Recuperator (3) and the stream (16) is then mixed with a leaner solution (17) to form the working solution (18). Finally, the stream is condensed and pumped to the boiler pressure (Larsen et al., 2014b).

Bombarda et al. (2010) in his research of Kalina cycle and ORC comparison for marine diesel engines stated that both cycles produce equal amount of power output, but the Kalina cycle requires very high maximum pressure for high thermodynamic performance and expensive no-corrosion materials as water-ammonia working fluid is used. Researches on the Kalina cycle for marine application is currently ongoing (Li et al., 2013; Bombarda et al., 2010).

Organic Rankine Cycle (ORC) is similar to a traditional steam Rankine cycle but uses an organic fluid like hydrocarbon or refrigerant as the working fluid. It is a closed loop thermodynamic cycle that consists of following processes (see Figure 5). Working fluid compressed in the pump and fed to the heat exchanger (1–2), where heat working fluid is evaporated by the exhaust gas heat (2–3). Evaporated working fluid expands in the turbine (4–5) which is mechanically connected by shaft to the generator and mechanical power is created. Further goes heat rejection/condensation stage where working fluid is cooled and condensed (5–6) and the cycle repeats.

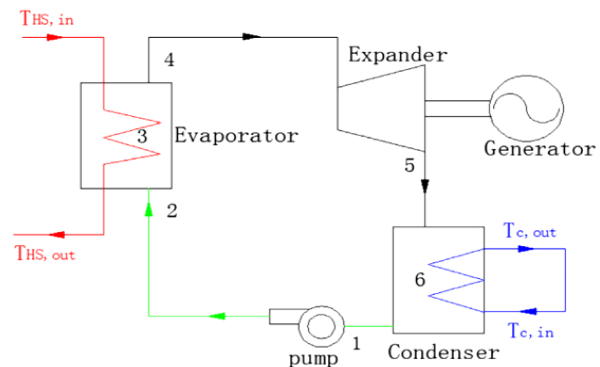


Figure 5. ORC working diagram

ORC makes possible to realize energy recovery from a low temperature heat source. Organic refrigerants or hydrocarbon compounds are used as a working fluid because of the significantly lower boiling point than water as result less input required to produce power (Tchanché et al., 2011; Bao & Zhao, 2013; Kim & Kim,

2017). Kaiko et al. compared ORC and Brayton cycles with marine application and researched that Brayton power output has increased more at high exhaust gas temperatures than ORC, as a result ORC is better in power generation at temperatures up to 680 °C, while Brayton cycle is better at higher temperatures, which makes it less attractive for marine application (Kaikko et al., 2019).

System efficiency can be optimized by selecting a proper working fluid operated at suitable working conditions to achieve maximum energy performance. Hung et al. researched eleven ORC working fluids and their thermodynamic performance, under investigation it was seen that suitable working conditions of various fluids can be identified based on their saturation vapour curves and response to the temperature energy source (Hung et al., 2010). Song et al. examined waste heat recovery with ORC of 996 kW marine diesel engine and achieved results that configuration is able to reach 10.2% power increase (Song et al., 2015). ORC most extensively studied cycle for marine application and as a result there is already applied in practice four in-service ships (Opcon Energy Systems AB, 2012; Viking Line, 2014; Marine Log, 2016; Kobelco Binary Cycle Power, 2019; Enogia Efficient Ship, 2019; Orcan Energy AG, 2019) (see Table 1). In service vessel with ORC heat recovery systems showed that fuel saving can be achieved from 4 to 15% which prompts to quick payback time of the system.

Table 1. List of Organic Rankine Cycle plants used in maritime transport

Ship Name (Year)	MV Figaro (2012)	Viking Grace (2015)	Arnold Maersk (2016)
Vessel type	PCTC	Cruise Ferry	Container
ORC Maker	Opcon	Climeon	Calnetix
Capacity	500 kW	150 kW	125 kW
Expander type	Twin-screw	Turbine	Radial turbine
Fuel savings	4–6%	Up to 5%	Up to 10–15%
	Asahi Maru (2017)	Orizzonte (2017)	Panera I & II (2018)
	Bulk	Fishing Vessel	Fast ferry
	Kobe Steel	Enogia	Orcan Energy
	125 kW	4.8 kW	154 kW
	Semi-hermetic screw	Microturbine	Screw
	3%	5%	6–9%

ORC already taken place in marine application, however not all aspects of practical application were investigated. Recent researches of ORC application are based on determined type marine diesel engines (mainly large, low speed engines) of the research where flexibility of this system application for various engine types in wide speed range and various working fluid is not discussed (Song et al., 2015; Lion et al., 2019; Yang, 2018;

Yang & Yeh, 2015; Mondejar et al., 2018; Nawi et al., 2019). Currently Authors are preparing such research of parametric and comparative analysis of cogeneration cycles for marine plants, which will include selection of cycle and working fluid according vessel type, engine type and load mode. Theoretical modelling of cycle has been performed with thermal engineering software Thermoflow, which allows accurately simulate thermodynamic performance of the modelled cycle.

Conclusions

Energy efficiency Design Index improvements has direct connection with CO₂ emissions from marine transport, improving this design parameter CO₂ emissions reduced accordingly. Waste heat recovery technology systems have more potential than other technologies due to the fact of combustion engine efficiency and wasted heat through exhaust gases. Organic Rankine cogeneration cycle has most attractive practical application for maritime transport compared to the Kalina and Brayton cycles. ORC and Kalina cycles are with a similar level of efficiency but Kalina cycle requirements are less attractive for marine application and Brayton cycle is efficient only at high temperatures. To achieve maximum efficiency of cogeneration cycles, selection of the fluid is required at variable operation conditions of marine transport. The authors of this study failed to find relevant researches of cogeneration cycle with practical selection guidelines for different types and sizes marine diesel engines in different power load modes with various selection of working fluids, therefore, due to the above mentioned fact the comparative studies of parametric analysis results are required for further studies with thermal engineering software in e.g. Thermoflow, to provide basics and guidelines of choosing cogeneration cycle according proper working conditions and parameters of the vessel.

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ORGANINIO „RANKINE“ CIKLO ANTRINĖS ŠILUMOS NAUDOJIMO JŪRINĖS PASKIRTIES DYZELIAMS TECHNOLOGIJOS APŽVALGA

T. Čepaitis, S. Lebedevas

Santrauka

Tarptautinės laivybos išmetamas CO₂ kiekis iki 2050 metų, anot Tarptautinės jūrų organizacijos, didės 50–250 %. 2011 m. įvestas energijos efektyvumo projektavimo indeksas (EEDI) yra pagrindinis reikalavimas, reguliuojant CO₂ emisijų kiekį jūrų transportui, kuris įsigalioja laipsniškai naujai statomiems laivams. Rengiant laivų projektus šio reikalavimo atitikčiai būtini technologiniai sprendimai. Atliekant naujausius tyrimus teigiama, kad jokios kitos technologijos neturi potencialo, lyginant su kogeneracinėmis sistemomis. Straipsnyje pateikiama trumpa energetikos efektyvumo projektavimo indekso tobulinimo technologijų jūrų transporte apžvalga, kogeneracinių sistemų pritaikymas jūrų transportui mažinant CO₂ emisijas. Pateikiama kogeneracinių ciklų lyginamoji analizė.

Reikšminiai žodžiai: EEDI, antrinė šiluma, kogeneracija, energijos efektyvumas, dekarbonizacija.