Marine application of Organic Rankine cycle waste heat recovery system for various type marine diesel engines in wide power range

24TH CONFERENCE „ENVIRONMENT PROTECTION ENGINEERING“

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Content of presentation

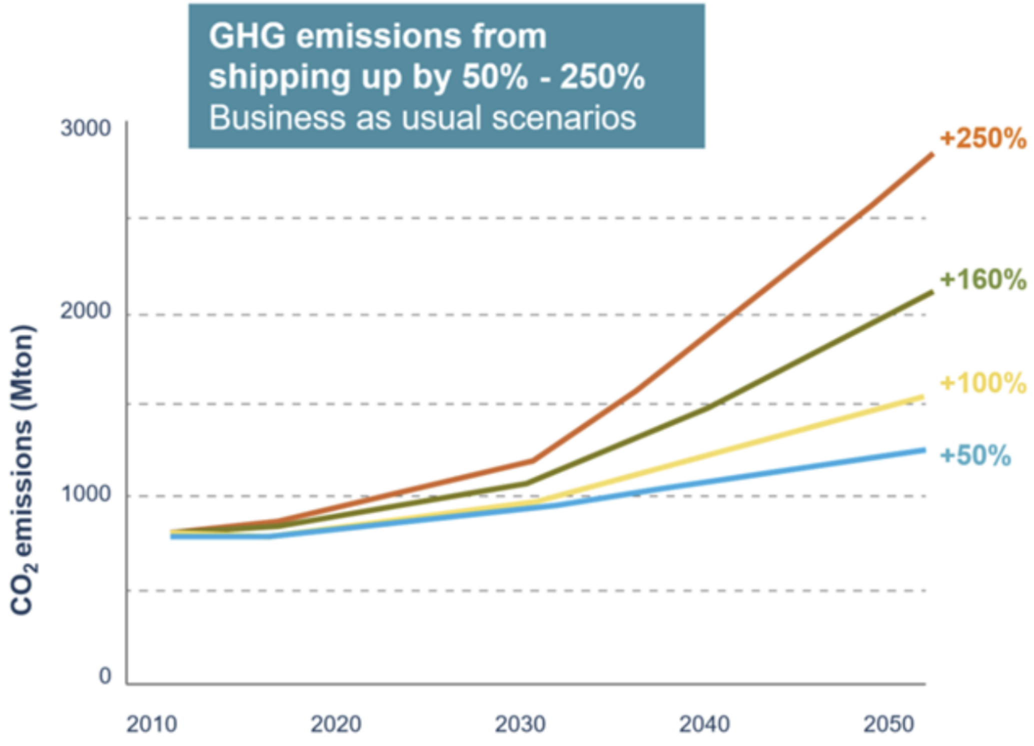
- Aim and objective of this study;
- Enviromental relevance of the problem;
- International Maritime Organization (IMO) Regulations;
- Potential of technical solutions;
- Waste heat recovery systems;
- Cogeneration cycles;
- Organic Rankine cycle justification;
- Practical application;

Aim and objectives of this study

- The aim of this study is to **review CO_2 emission reduction of maritime transport technologies**, introduce heat recovery systems with **cogeneration cycles** and **compare their practical application** for maritime transport.
- Objectives:
- Describe maritime transport impact to the enviroment;
- Compare potential of CO_2 *reduction* technologies;
- Compare cogeneration cycles practical application for maritime transport;

Enviromental relevance of the problem

- The IMO third greenhouse gas emission study envisions that even with predicted increase in ship average efficiency of 40% and **without any** further **regulations**, CO_2 emissions from international shipping could increase between 50-250% by 2050 because of increasing cargo amount transported each year by maritime sector .
- 90% of ship are power by diesel engines which burns heavy fuel oil (HFO) and release CO_2 emissions.



Evolution of GHG emissions from shipping depending on various economic growth and energy development projections. Source: Third IMO GHG Study (2014)

International Maritime Organization (IMO) Regulations

- MARPOL convention with amended protocol Annex VI of International Convention for the Prevention of Pollution from Ships regulates emissions from ship exhaust of NO_x, SO_x and PM
- To ensure the decrease of GHG emissions for new built ships primary CO_2, Marine Environment Protection Committee (MEPC) adopted amendments to MARPOL Annex VI in which the Energy Efficiency Design Index (EEDI) was made **mandatory** for new.

International Maritime Organization (IMO) Regulations

- EEDI regulation is an important measure tool to keep improving international shipping efficiency.
- There are several phases of EEDI level implementation targeted for new ships:
  Phase 0 to have a design efficiency at least equal to the baseline
  Phase 1 at least **10%** below reference line
  Phase 2 design efficiency required to be **20%** below baseline. Phase 3 is set of **30%** reduction of the carbon emission per nautical mile and transported cargo unit in 2025.

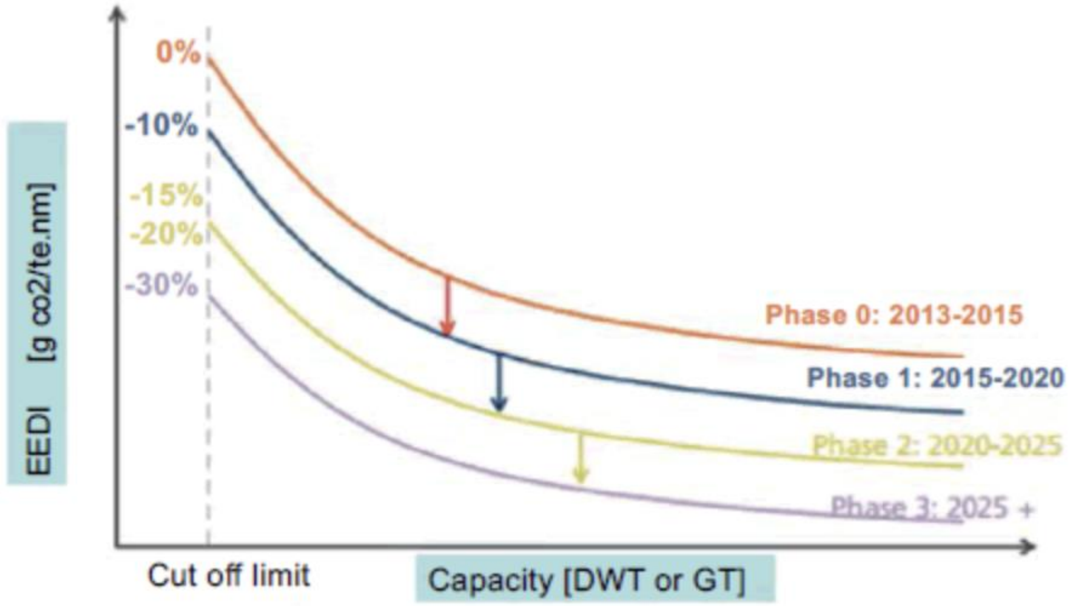


Figure 1: Concept of Required EEDI, reduction factor, cut off limits and EEDI Phases, Note: Reprinted from Module 2 - Ship Energy Efficiency Regulations and Related Guidelines, IMO.

Potential of technical solutions

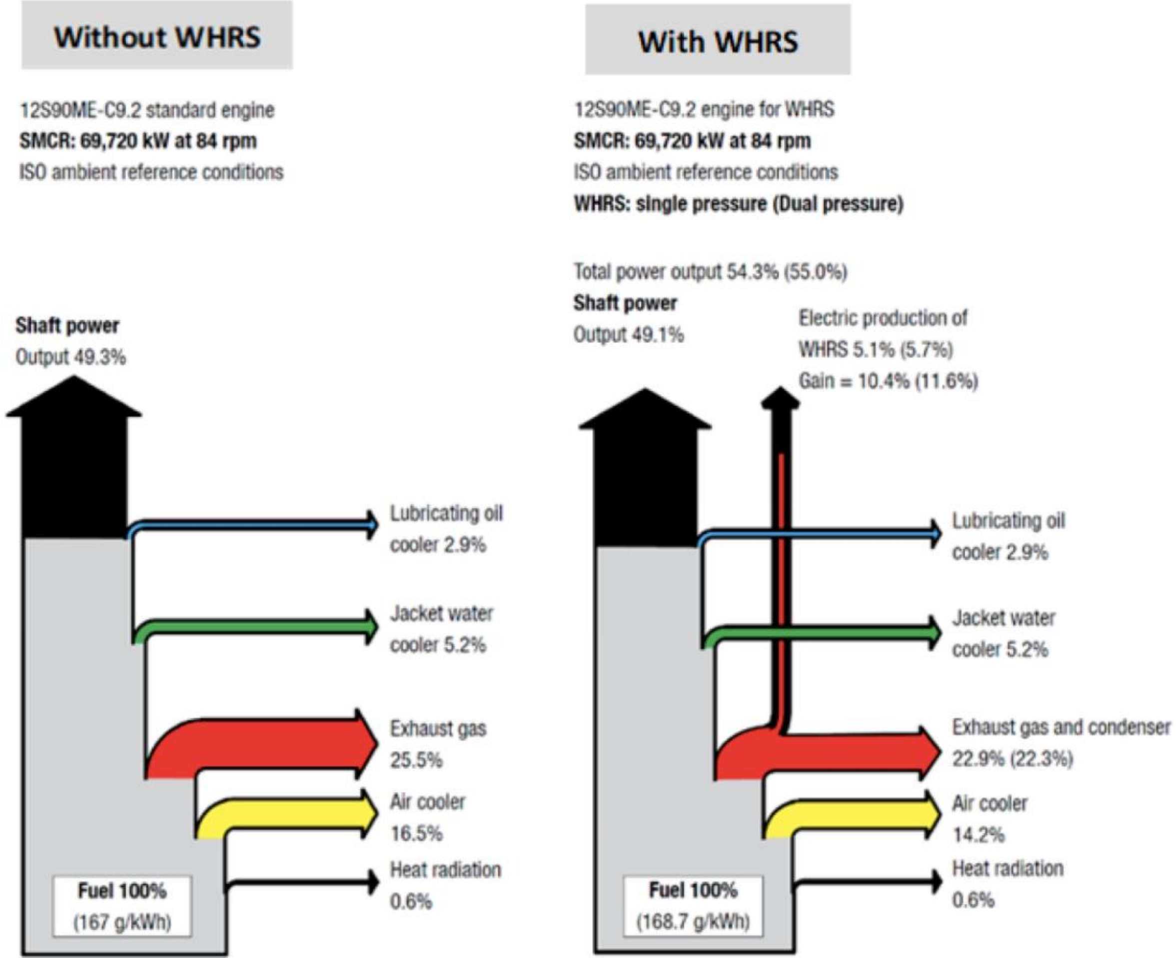
- There are multiple solutions for fuel saving divided to **operational measures** (voyage execution, engine monitoring reduction of auxiliary power, weather routing, hull/propeller polishing, trim/draft optimization, slow steaming and etc.) and **design measures** (more efficient engines, propellers, hull design improvements, wind propulsion).
- Also there is 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.

Potential of technical solutions

- DNV GL included these design 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

Waste heat recovery systems

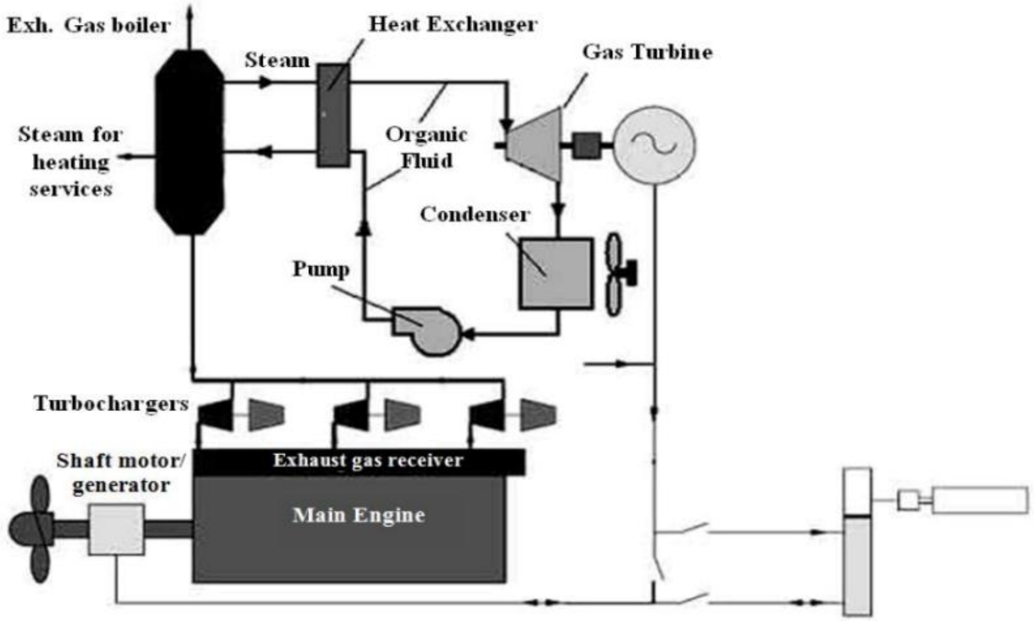
- Recent several studies, reports and papers concludes that **none of mentioned measures could have** energy potential compared to the waste heat recovery systems.
- Modern diesel engines have up to 50% efficiency of total fuel energy supplied and other 50% is lost to surrounding as heat losses.



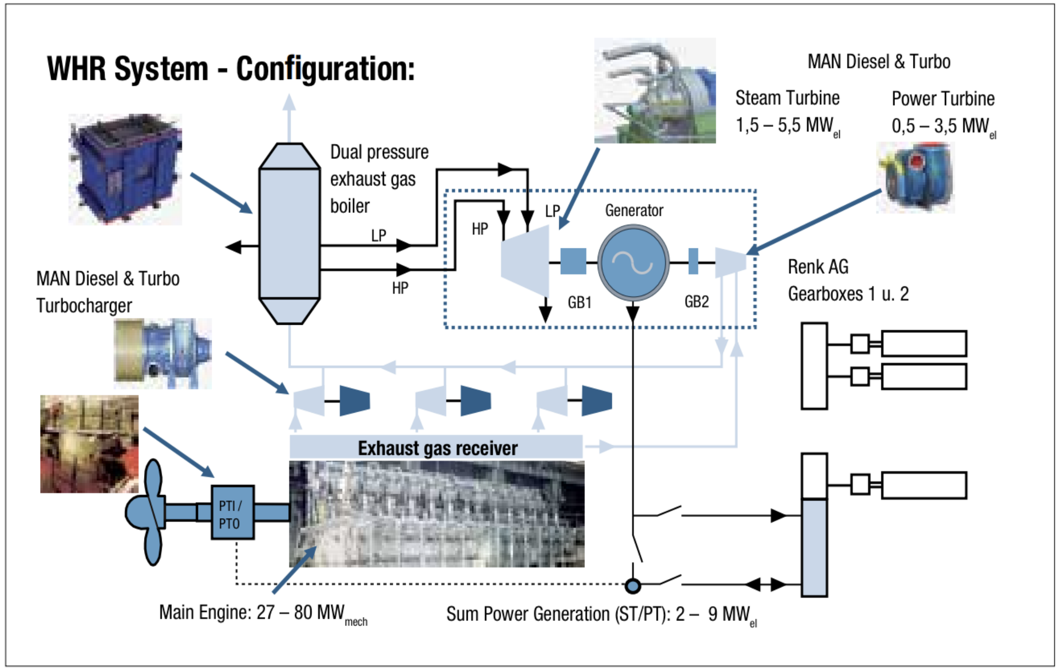
Waste heat recovery systems

- It is apparent that **waste heat recovery systems have more potential and reserves than any other technology compared**. Biggest marine machinery manufacturers offers multiple WHR systems.

WARTSILA & TURBODEN WHRS

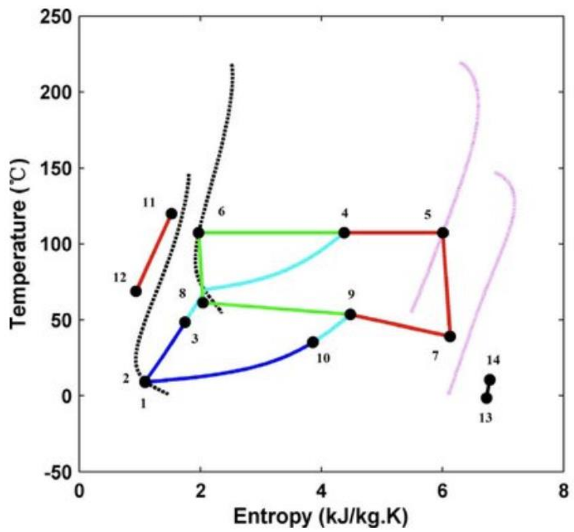


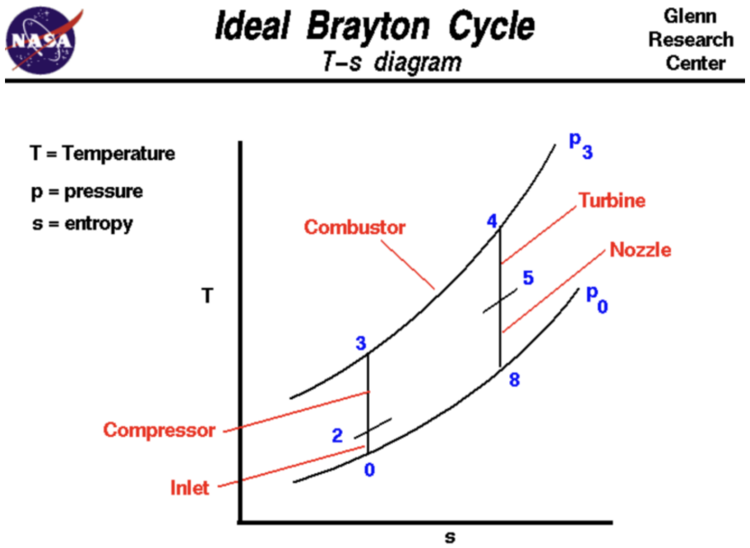
MAN WHRS

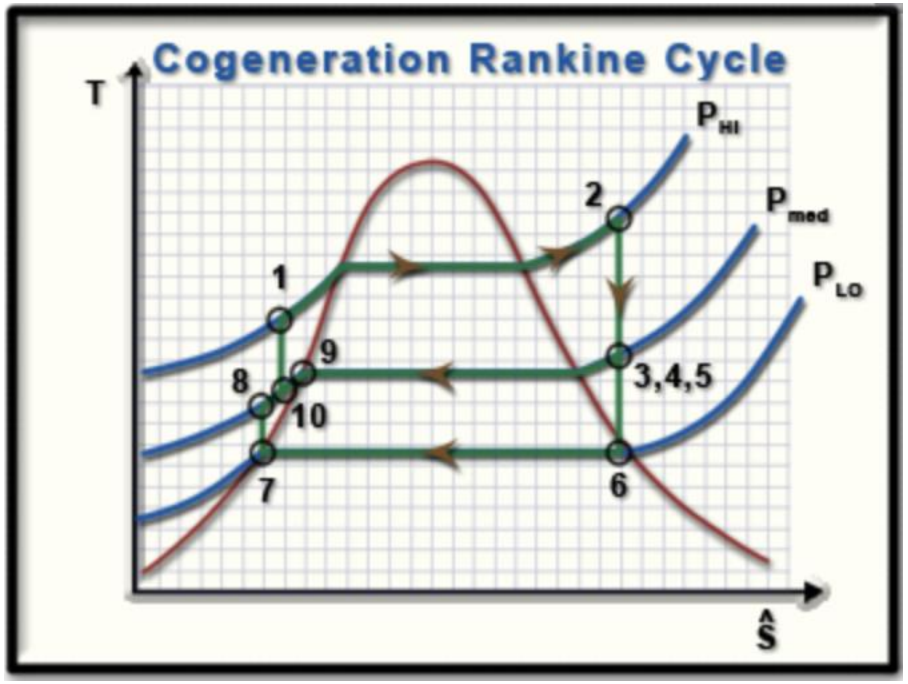


Cogeneration cycles

- Waste heat recovery is based on cogeneration cycles:
- Brayotn cycle
- Kalina cycle
- Organic Rankine cycle

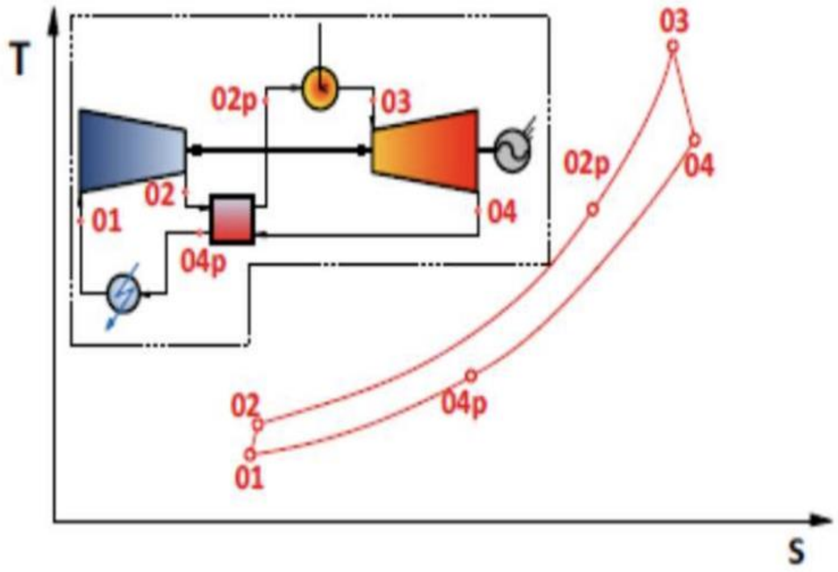






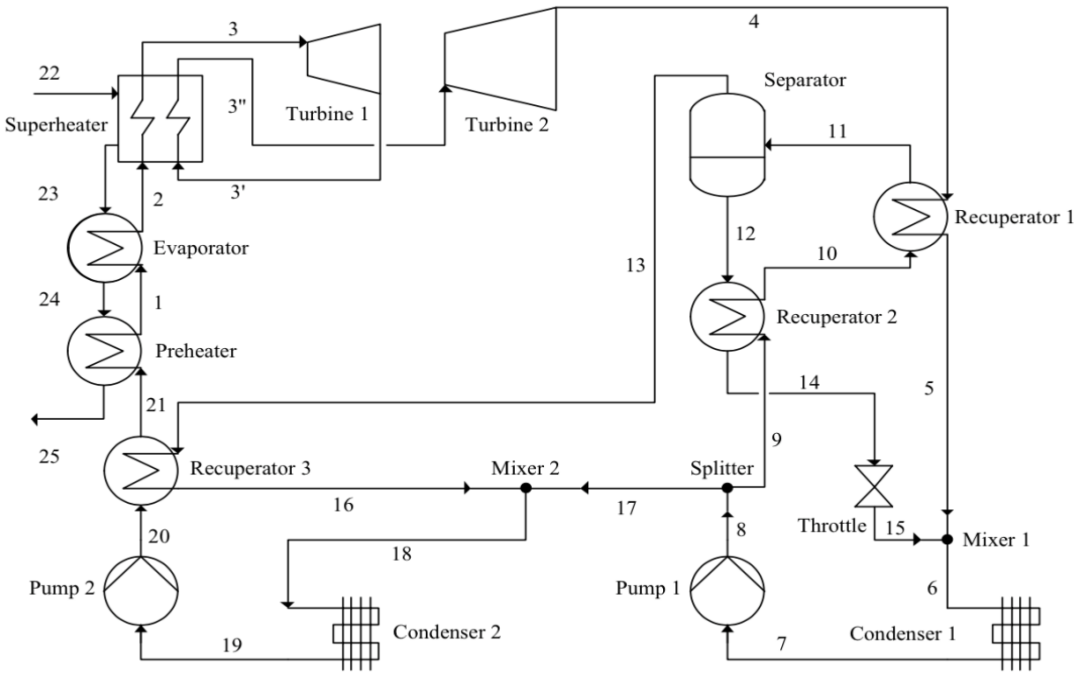
Brayton cycle

- In water transport, a closed gas turbine Brayton cycle is used, where the heat released in the combustion chamber and release of energy into the environment as the exhaust gas are replaced by heat exchangers to supply or extract heat. The energy generated by the cycle is determined by the difference.
- 1-2 compression
- 2-2p recuperator
- 2p-3 heat source
- 3-4 expansion
- 4-4p working fluid preheat in recuperator
- 4p-1 heat elimination (cooling)



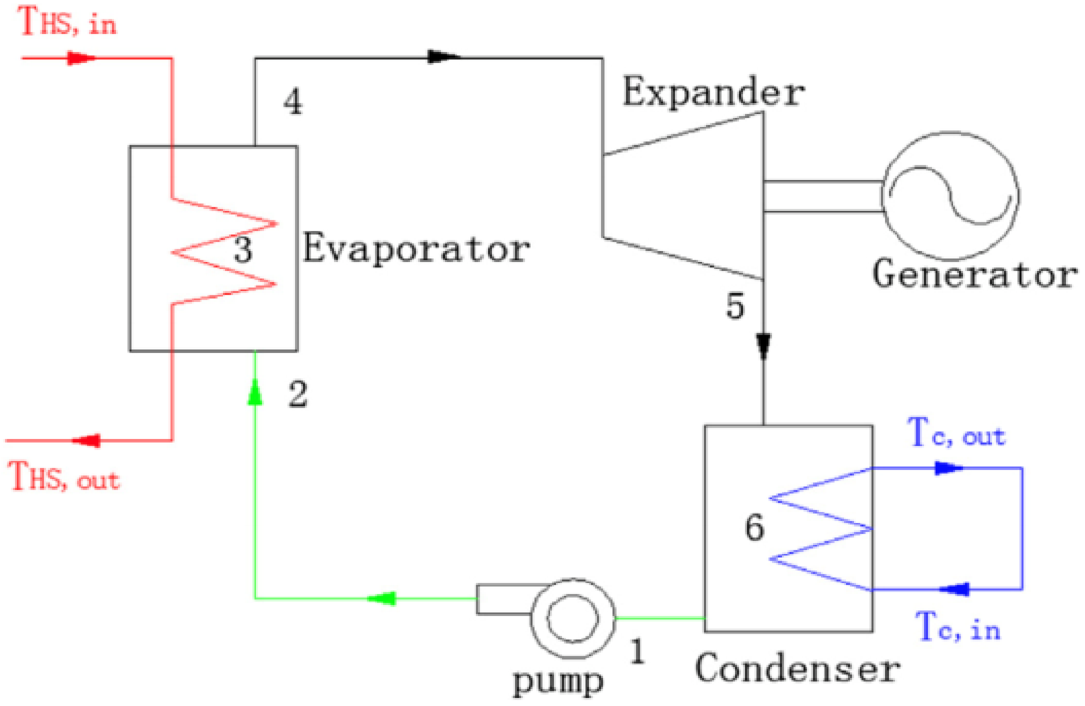
Kalina cycle

- The Kalina cycle is a new concept in heat recovery and power generation, which uses a mixture of 70% ammonia-30% water. It is modified form of Rankine cycle.
  1-3 heat inlet;
- 3-4 working fluid compression;
- 4-5 heat transfer through recuperator;
- 5-6 stream mix with ammonia;
- 6-7 condensation;
- 7-8 intermediate pressure level; stream divided in two paths;
- 9-11 heat added in recuperators;
- 11-12 separated lean liquid;
- 11-13 separated rich vapour;
- 13-20 preheat, mixed leaner solution;



Organic Rankine cycle

- Organic Rankine cycle (ORC) It is a closed loop thermodynamic cycle that consist of following processes:
  1-2 working fluid compression;
  2-3 heat admission;
  4-5 working fluid expansion;
  5-6 heat rejection/condensation;
- Bombarda in his research stated:
  - Kalina and ORC produce equal power output
  - But the Kalina cycle requires very high maximum pressure for high thermodynamic performance and expensive no-corrosion material.



Organic Rankine cycle

- ORC most extensively studied cycle for marine application as a result there is already applied in practice for in-service ships. In service vessel with ORC heat recovery systems showed that fuel saving can by achieved from 4 to 15% which prompts to quick payback time of the system

Ship Name (Year)	MV Figaro (2012)	Viking Grace (2015)	Arnold Maersk (2016)	Asahi Maru (2017)	Orizzonte (2017)	Panerai I & II (2018)
Vessel type	PCTC	Cruise Ferry	Container	Bulk	Fishing Vessel	Fast ferry
ORC Maker	Opcon	Climeon	Calnetix	Kobe Steel	Enogia	Orcan Energy
Capacity	500 kW	150 kW	125 kW	125 kW	4.8 kW	154 kW
Expander type	Twin-screw	Turbine	Radial turbine	Semi-hermetic screw	Microturbine	Screw
Fuel savings	4–6%	Up to 5%	Up to 10–15%	3%	5%	6–9%
References	[6]	[7]	[8]	[9]	[10]	[11]

List of Organic Rankine cycle plant used in maritime application

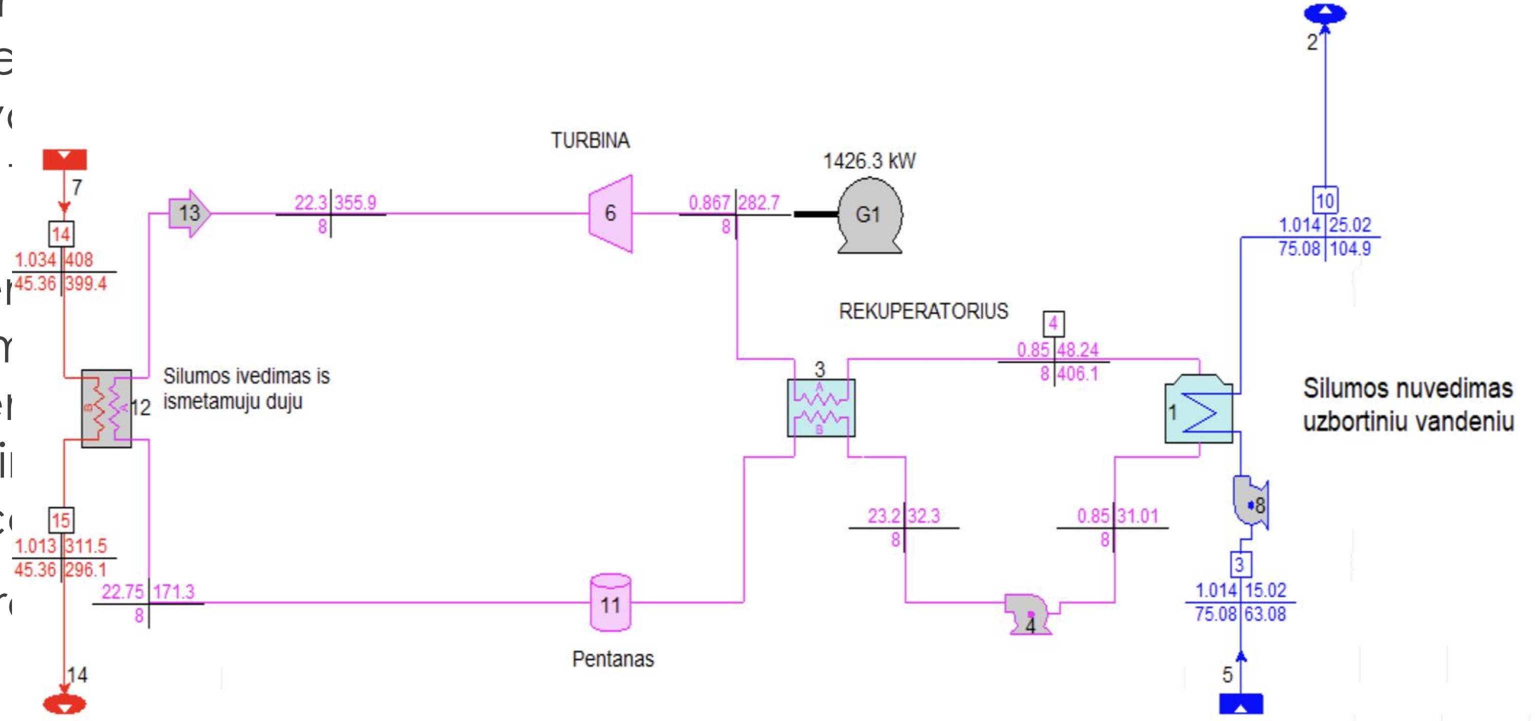
Organic Rankine cycle

- Orc provide wide selection of working fluids.
- The working fluid selection is of key importance on the thermal performance of the ORC recovery system. Generally, the working fluids can be classified into the following three categories:
- wet fluids, dry fluids and isentropic fluids.

			at 0.1MPa (kJ/kg)			
R11	Trichloromonofluoromethane	137.37	181.49	471.11	4.4076	Isentropic
R12	Dichlorodifluoromethane	120.91	166.3	385.12	4.1361	Isentropic
R13	Chlorotrifluoromethane	104.46	149.47	302	3.879	Wet
R14	Tetrafluoromethane	88.01	134.54	227.51	3.75	Wet
R21	Dichlorofluoromethane	102.92	217.76	451.48	5.1812	Wet
R22	Chlorodifluoromethane	86.468	233.92	369.295	4.99	Wet
R23	Trifluoromethane	70.01	239.552	299.293	4.832	Wet
R32	Difluoromethane	52.02	382.14	351.255	5.782	Wet
R41	Fluoromethane	34.03	489.164	317.28	5.897	Wet
R113	1,1,2-Trichloro-1,2,2-Trifluoroethane	187.38	144.45	487.21	3.3922	Dry
R114	1,2-Dichloro-1,1,2,2-Tetrafluoroethane	170.92	136.06	418.83	3.257	Dry
R115	Chloropentafluoroethane	154.47	116.49	353.1	3.12	Isentropic
R116	Hexafluoroethane	138.02	117.09	293.03	3.048	Wet
R123	2,2-Dichloro-1,1,1-Trifluoroethane	152.93	170.35	456.831	3.6618	Dry
R124	1-Chloro-1,2,2,2-Tetrafluoroethane	136.5	165.99	395.425	3.6242	Wet
R125	Pentafluoroethane	120	164.25	339.173	3.6177	Isentropic
R134a	1,1,1,2-Tetrafluoroethane	102.03	217.16	374.21	4.0592	Isentropic
R141b	1,1-Dichloro-1-Fluoroethane	116.9	222.88	477.5	4.212	Dry
R142b	1-Chloro-1,1-Difluoroethane	100.5	223.43	410.26	4.055	Isentropic
R143a	1,1,1-Trifluoroethane	84.04	226.82	345.857	3.761	Isentropic
R152a	1,1-Difluoroethane	66.05	330.18	386.411	4.5167	Wet
R236ea	1,1,1,2,3,3-Hexafluoropropane	152	165.32	412.44	3.5019	Dry
R236fa	1,1,1,3,3,3-Hexafluoropropane	152	160.48	398.07	3.2	Dry
R245ca	1,1,2,2,3-Pentafluoropropane	134	201.15	447.57	3.925	Dry
R245fa	1,1,1,3,3-Pentafluoropropane	134	196.88	427.2	3.64	Dry
R417a	46.6% R125, 50% R134a, 3.4% R600 (by weight)	106.75		360.19	4.036	Isentropic
R422a	85.1% R125, 11.5 R134a, 3.4% R600a (by weight)	113.6		344.9	3.747	Isentropic
R422d	65.1% R125, 31.5% R134a, 3.4% R600a (by weight)	109.94		352.71	3.903	Isentropic
R423a	52.5% R134a, 47.5% R227ea (by weight)	125.96		372.64	3.587	Isentropic
R170	Ethane	30.07	489.79	305.33	4.8718	Wet
R290	Propane	44.09	426.232	369.825	4.2476	Isentropic
R600	Butane	58.12	386.01	425.125	3.796	Dry
R601	Pentane	72.1	357.89	469.7	3.37	Dry
	Cyclohexane	84.16	356.3	553.64	4.075	Dry
	Benzene	78.11	394.96	562.05	4.894	Dry
	Toluene	92.14	361.007	591.75	4.1263	Dry
R717	Ammonia	17.02	1370.25	405.4	11.333	Wet

Practical application

- As the authors failed to find relevant r
of Organic Rankine cycle applicatior
different types and sizes marine diese
in different power load modes with v
selection of working fluids, based on
the **<u>aim of further study</u>** is to prepare
comparative research and with giver
guideline in choosing the ORC systen
most appropriate working fluid deper
the type of the engine and the worki
mode of the ship for practical applic
- Results will be modeled using softwar
Thermaflow.



Conclusion

- It is important to decrease CO_2 emission because of the maritime transport sector due to increasing cargo amount transported each year, whithout any regulation, emission can increase drastically;
- Waste heat recovery systems has the most potential (up to 50%) compared and it can be used parallel with other technologies;
- Cogeneration cycles are effective way to increase ship efficiency. Based on recent studies Organic Rankine cycle is attractive choice of practical application for marine transport, but further studies of comparative research of cogeneration cycles adaptability for various types of ship with different load modes and selection of working fluid is needed.