SEA TRIALS OF AN ORGANIC TRIANGLE SYSTEM (OTC) FOR WASTE HEAT RECOVERY

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ABSTRACT

The organic triangle cycle (OTC) incorporates a simple liquid counter-current heat exchanger, eliminating the “pinch point” limitation of the heat input to organic Rankine cycle (ORC) systems. A flashing liquid expander is used to generate power from the heated high pressure liquid. Improvements in power production from heat sources of as much as 20 to 40% have been calculated, subject to the efficiency of the flashing liquid expander and the minimum allowable return temperature of the heat source (DiPippo,2007). Several applications of a flashing liquid expander known as the Variable Phase Turbine (VPT) were successfully addressed; including the replacement of expansion valves in chillers and industrial refrigeration and in a geothermal OTC system. These applications substantiated the efficiency and reliability of the VPT for OTC applications (Welch *et a*l, 2011)

Recently the VPT was applied to an OTC system for waste heat recovery from a shipboard engine. The rated engine output was 17,650 kW. The source of waste heat was hot air from the turbocharger compressor. The shipboard propulsion engine was manufactured by Mitsui E&S Machinery Co., Ltd. (MES) to power a bulk carrier ship. The OTC was manufactured by MES, factory tested, and subsequently installed with the engine on the ship.

Performance and design of the OTC system for the factory test and sea trials are provided. The system produced power from air at a range of 183 C to 191 C. The hot air was produced from a turbocharger compressor of the propulsion engine. Maximum power produced by the VPT was 234 kW. The OTC system was operated for 4,079 hours during a sea trial. The system was insensitive to pitch and roll of the ship.

After shakedown and qualification tests the system was demonstrated for six (6) commercial voyages of the ship. The system was operated for 2079 hours during these voyages. The generated power was fed into the ship grid. The power required from the ship diesel electric generator and hence, greenhouse gas emissions for the ship were reduced.

Design of the installation, controls and electrical system to ensure compatibility with the ship systems is provided. Performance, reliability and operational experience for the sea trial are reported. Reduction in carbon emissions from reduction of the power required by the ship diesel electric generator is estimated.

The sea trials of the OTC demonstrated its reliability for marine applications. Additional marine waste heat recovery possibilities include power generation from the propulsion engine exhaust and cooling water, as well as supercharger waste heat.

1. INTRODUCTION

A major source of carbon dioxide (CO_2) emissions is the maritime industry. The 2019 annual emissions were estimated to be 940 million tons by the European Commission (European Commission, 2019). A total of 11,600 ships were estimated to consume 44 million tons of fuel during that year. The main sources of these emissions are the main ship engines and the diesel electric generator for ship power. In addition to the CO_2 emissions these engines are a large source of waste heat. Conversion of the waste heat from the main engine to electric power for the ship grid can avoid emissions from the ship diesel generator.

A new approach, first proposed in 1977, (Hays and Neal, 1977), employs a flashing liquid expander known as the Variable Phase Turbine (VPT) for the power conversion device. This enables a simple counter-current liquid heat exchanger to be used. The resulting heat transfer from a sensible heat liquid or gas source is a perfect "glide", maximizing the heat input to the energy conversion cycle. The key component of the cycle is the flashing liquid expander. Several attempts to operate other expanders with the required two-phase flow have not been successful to date (Hays *et al*. 2017b). However, the VPT has demonstrated efficiency and reliability suitable for successful application to the OTC.

This conversion cycle differs from the Rankine cycle in the triangular shape of the heating, expansion and condensing paths, hence the name organic triangle cycle or OTC. Other advantages include the insensitivity to motion of the liquid heat exchanger and the VPT with a conventional submerged refrigerant generator eliminating a gearbox, lube oil system, shaft seals and a seal system conventionally required by ORC systems. (Hays *et al*. 2017b)

This paper will document the sea trials for application of the OTC with a VPT to recover waste heat from a main ship engine. The goals of the program were to demonstrate the reliability of the VPT and OTC in for extended period of time and the successful integration of the OTC with the main engine and ship systems.

2. APPLICATION TO MARINE MAIN ENGINE

A schematic of the OTC for the marine application of the Variable Phase Turbine is shown in Figure 1; the nomenclature used by MES for this marine project is the Variable Phase Cycle (VPC). That nomenclature will be used in the following text. The working fluid was R-245fa. Sub-cooled condensate from the Condenser and Inventory tank is pressurized to a highly sub-cooled state by the Circulation pump. The pressurized liquid flows through the VPC heat exchanger where it is heated by the Scavenging hot air. The heated high pressure fluid flows through a control valve and is flashed in the Two-phase nozzle. The resulting high velocity vapor-liquid jet drives a Two-phase turbine generator producing power for the ship grid. The exhaust from the Two-phase turbine at low pressure is condensed in the Condenser which is cooled by sea water.

The arrangement with the ship engine is shown in Figure 2. The VPC heat exhanger is installed in the scavenging air cooling casing. The VPC heat exchanger directly receives the hot air flow. The cooled air flows through the Air cooler to the engine. The Air cooler, which is cooled by sea water, is installed below the VPC heat exchanger. When the VPC system is not operating the air cooler removes the heat from the scavenging air.

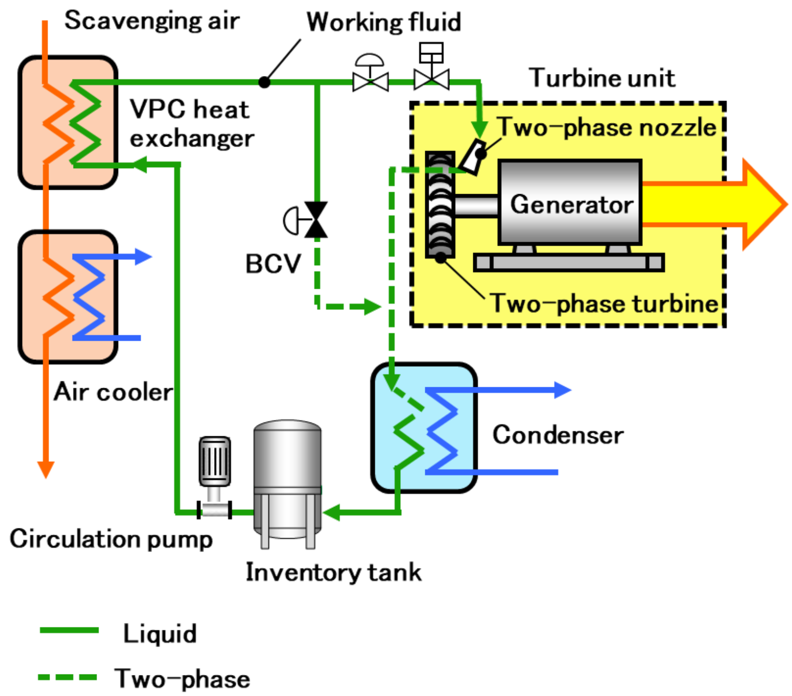

Figure 1: Schematic of VPC System for Ore Carrier

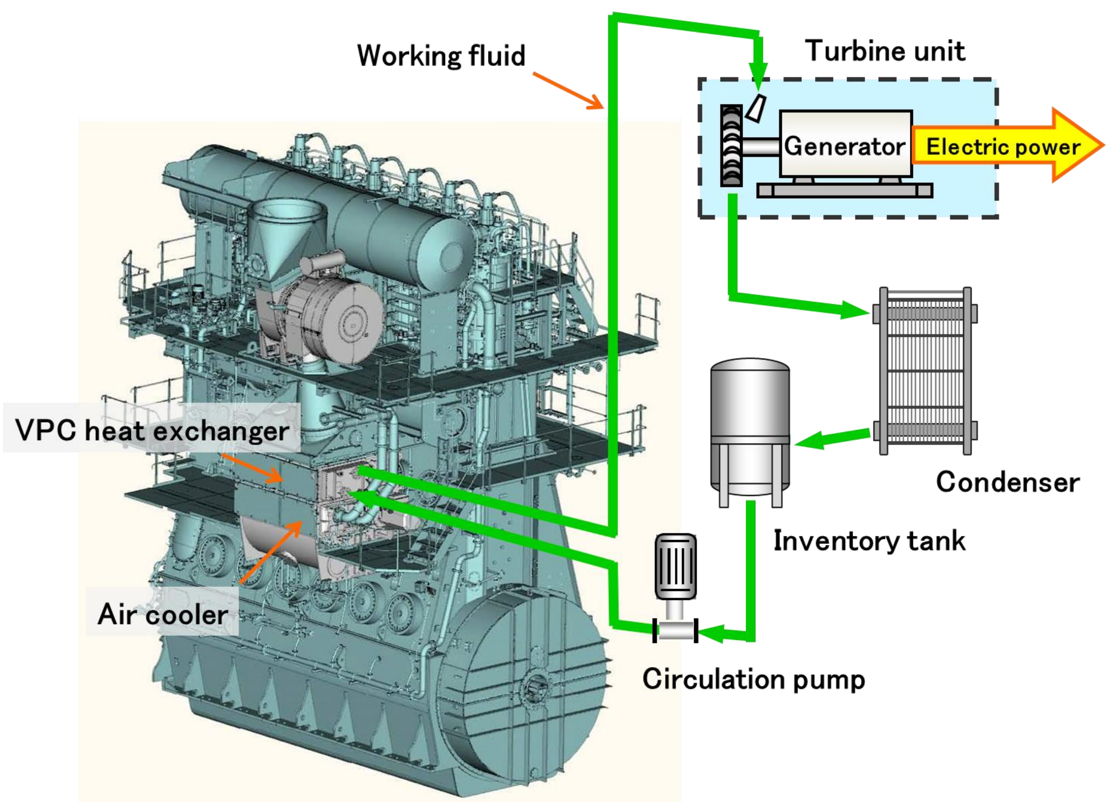

Figure 2: Installation of VPC with Main Engine

The VPT unit is installed on the deck of the engine as shown in Figure 3 and viewed from the generator end. The VPT directly drives the generator which in turn is directly connected to the ship grid. The VPT is compact and installed such that it is easily accessible for maintenance.

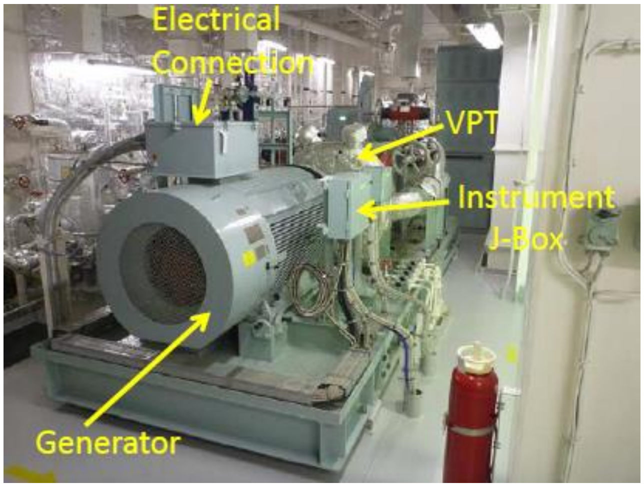

Figure 3: VPT Installation on Ore Carrier

The VPC system was applied to the ore carrier and the demonstration test was carried out for multiple voyages of this ship. The optimum arrangement to the engine room was examined and the system installed on the ship. The system and its controller were designed to satisfy the following points, which were successfully demonstrated:

1. Non-interference with operation of the ship and the operation of the main engine
2. Parallel operation of the VPC power generation controls with the main generator
3. Reliability and durability in the actual sea environment

Table 1 shows the specifications of the turbine generator and the heat exchanger and pump

Table 1: VPC Equipment Specifications

Equipment	Item	Specification
Turbine	Type	Single Stage Two-Phase Impulse Turbine
Turbine	Maximum Output	275 kW
Turbine	Speed at Maximum Load	3640 rpm
Turbine	Shaft Seal Type	Air Pressurized Double Mechanical Seal
Generator	Type	Three Phase Induction Generator
VPC Heat Exchanger	Type	Plate Fin Type Heat Exchanger
Condenser	Type	Twin-Plate Type Heat Exchanger
Circulation Pump	Type	Single Stage Vertical Axis Centrifugal Pump

3. OPERATION OF THE VPC

The normal start-stop procedure was performed in an automatic sequence from the VPC system operation panel. The system started by an automatic sequence. In the case of an emergency such as abnormal behavior of the turbine unit the VPC system automatically shut down safely and disconnected from the ship grid.

In the operation mode the VPC system is divided into three main parts

1. Bypass mode - After starting the main engine and VPC system the entire working medium flows through the bypass control valve. The thermal energy absorbed by the working medium is recovered by the condenser and released into the cooling water.

2. Normal mode – The circulating pump introduces the entire fluid into the turbine. The turbine generator generates electricity and power to the onboard electrical system.

3. Partial mode - In the partial bypass mode part of the operating medium flows through the bypass control valve. The turbine generator generates power that is sent to the ship system. If the turbine inlet pressure is too high the bypass flow is actuated to relieve pressure.There is no governing function in the turbine in the VPC system as it is not necessary. The induction generator is connected to the shipboard grid and so the frequency of the grid provides speed control for the turbine generator.

Startup of the VPT is shown in figure 4. Operation in the Bypass mode has reached steady conditions before starting the VPT. The start button is actuated to open the VPT control valve. The valve starts opening admitting flow to the VPT (dash and dot). The bypass valve is automatically closing to maintain a constant pressure and total flow (long dash). The VPT flow and speed are increased until synchronous speed is reached (solid line). At this point the generator breaker is closed, with a reactor to limit inrush current, and the VPT produces power to the ship grid (short dash). The control valve continues opening until all of the flow is admitted to the VPT and the power is maximized.

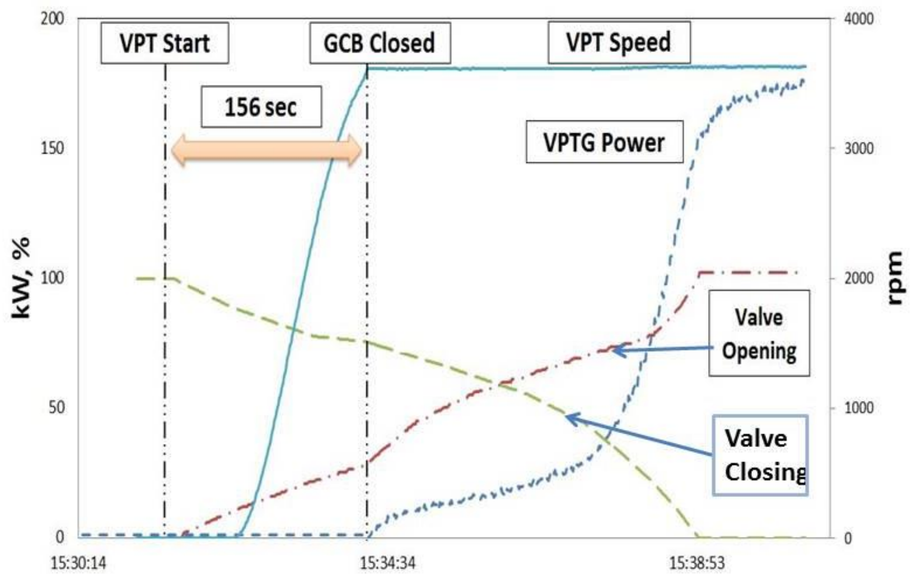

Figure 4: Dynamic Sequence of VPC Startup

Voltage and frequency fluctuations are to be maintained within those specified limits as shown below.
For transient fluctuations;
- Voltage (Transient): ± 20 % (within 1.5 sec)
- Frequency (Transient): ± 10 % (within 5 sec)

For permanent fluctuations;
- Voltage (Permanent): - 10 % , + 6 %
- Frequency (Permanent): ± 5 %

The dynamic behavior of the main bus voltage and frequency when the breaker is closed is shown in Figure 5. The voltage and frequency fluctuations damp out in ~2 seconds. The ship power system accommodated the fluctuations without changing operation.

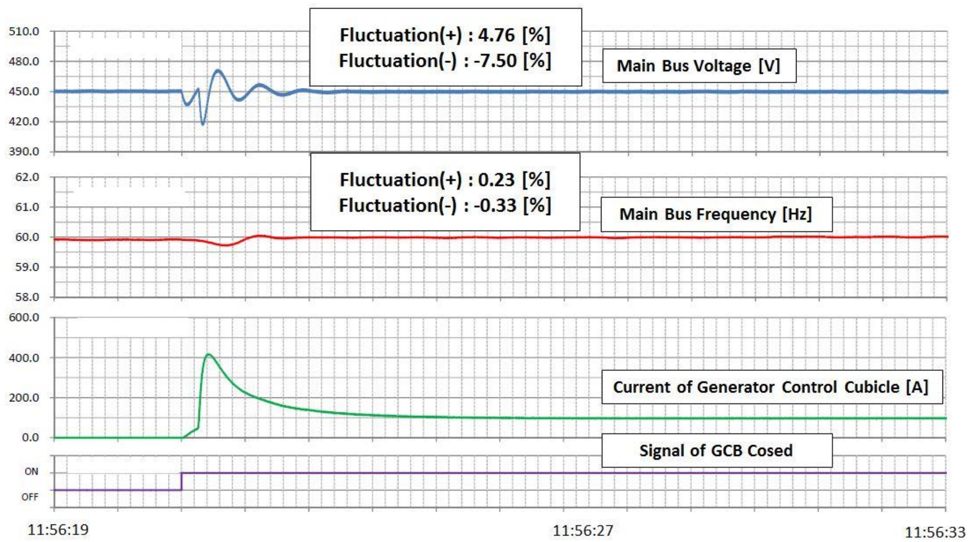

Figure 5: Response of Ship Electrical System to VPT Connection

4. EXPERIENCE DURING SEA TRIALS

The VPC system was operated with the ship engine in the MES factory in Tamano, Japan. 245 kW were generated and the VPC system was qualified for installation and operation in the ore carrier. After installation the system was operated for shakedown testing. The shaft seals were repaired in order to find an O-ring material which resists both R245fa and sealing oil. The original seal materials were FKM and NBR. These were replaced with FFKM for high temperatures and CR for low temperature. The system was operated to obtain ClassNK approval from Nippon Kaiji Kyokai.

During subsequent sea trials the valve seal failed due to chemical attack and was replaced with PTFE. (These problems favor the application of hermetic turbine generator technology, (Hays et al., 2017c) for future installations.) The total operating time logged during shakedown tests and qualification tests was 1350 hours.

After repairs and qualification the VPC system was operated during six (6) voyages totaling an additional 2729 hours with no further problems. Table 2 summarizes the onboard operation during sea trials.

Table 2: Operating Experience during Onboard Sea Trials

Function	Results	Operating Hours
Shakedown and Class Qualification Operation	Class Certificate Issued. Repairs to Seals Completed	1235
Initial Sea Voyage	Repairs to Seals Completed	115
First Sea Voyage	Continuous Operation	439
Second Sea Voyage	Continuous Operation	373
Third Sea Voyage	Continuous Operation	503
Fourth Sea Voyage	Continuous Operation	430
Fifth Sea Voyage	Continuous Operation	503
Sixth Sea Voyage	Continuous Operation	481

The operation of the VPT output power during the 10-day segment of the sixth ship voyage is shown in figure 6. Power output ranged from ~150 kW to 220 kW depending upon the Main engine load. For this voyage the Main engine operated from ~60-80% of full load (17,650 kW output at 100%). Fluctuations in the VPT power output of 70 kW resulted from the fluctuations in engine power of 3530 kW which varied the heat from the turbocharger available for conversion by the VPT.

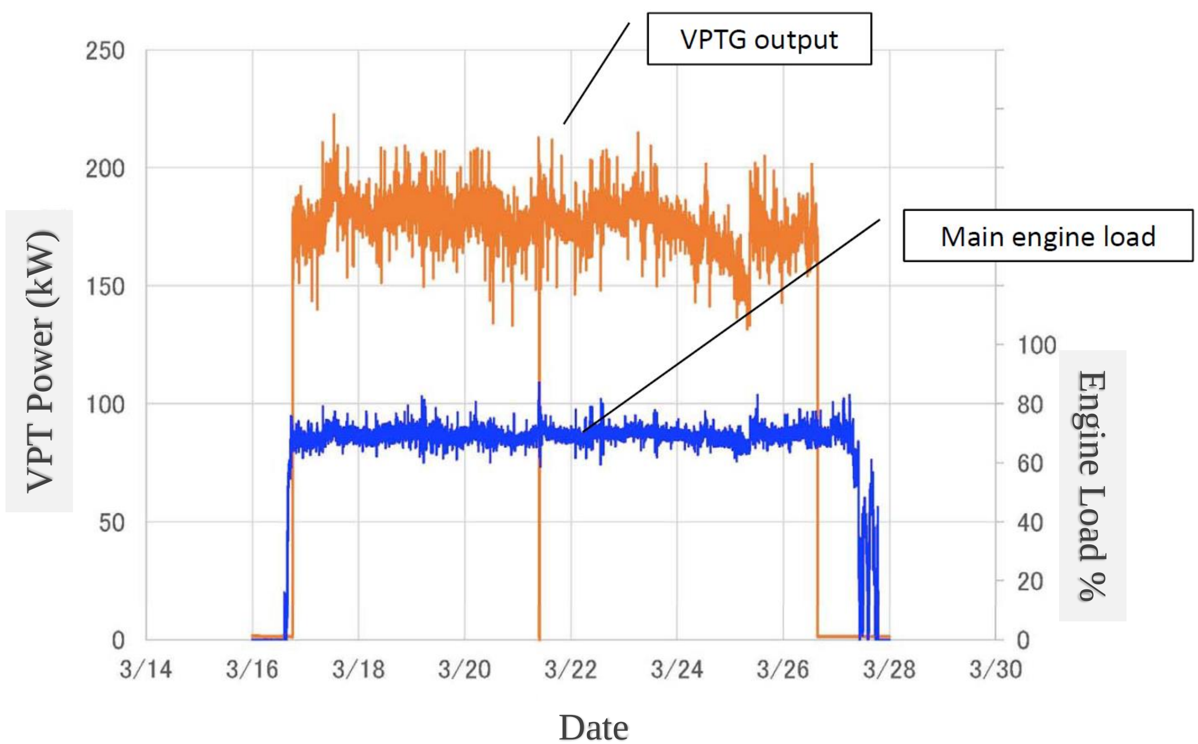

Figure 6: Power Output of VPT and Main Engine During Sixth Voyage

A teardown and inspection of the VPC system was conducted by MES at the Tamano factory and revealed no damage. Some residue was found from the aforementioned internal seal leakage. The turbine is shown in Figure 7. Importantly, no damage or erosion to the blades was found.

Figure 7 VPT Rotor after 4000 hour Sea Trial Operation

5. PERFORMANCE

The VPC test system was a proof of concept system to demonstrate the VPT stability and durability with flashing working fluid; and compatibility of the system with operation of the ship and main engine during actual sea voyages. Emphasis was not given to maximizing efficiency. The design goal was a net system efficiency of 4.1%. However the condenser pressure was higher than anticipated. VPT efficiency suffered due to a low value of U/C and the pump efficiency was lower than planned. The measured performance is summarized in Table 3. Also shown are the performance of an OTC system for the same scavenging flow conditions with a hermetic generator; designed with the design code verified by a geothermal OTC system (Welch, *et al*, 2011). Performance can also be enhanced if the once through heat exchanger is designed to provide some two-phase flow at the outlet. That case is also provided in Table 3. The two-phase flow case produces more power by reducing the pump power and increasing performance of the VPT.

Table 3: Comparison of VPC Performance with Optimized OTC Systems for Identical Scavenging Air Conditions and Condenser Temperature

Air Temperature and Heat Input Deg C; kW	VPT Inlet Temp Deg C	VPT Inlet Mass Flow and Vapor Fraction kg/s; Mass Fraction	VPT Inlet Pressure bara,	VPT Exit Pressure bara	VPT Power kW	System Net Power kW	System Efficiency percent
191; 3,578	137	24.5; 0	26.2	2.3	234	126	3.5
191; 3,578	137	24.3; 0	27.4	2.7	366	294	8.2
191; 3,578	137	20.7; 0.3	26.8	2.7	402	342	9.6

The reduction in emissions of CO_2 from the diesel generator during the voyages was approximately 217 tonnes. Implementation of the optimized OTC systems would have reduced the emissions by 505 tonnes and 588 tonnes respectively. Table 4 summarizes the basis for the reductions in CO_2.

Table 4: Reduction in CO_2 Emissions

VPC Net power [kW]	Fuel saving of diesel generator *1 [ton/day]	CO2 reduction per day *2 [ton/day]	CO2 reduction per 2729h *3 [ton]
126	0.635	1.91	217
294	1.482	4.445	505
342	1.724	5.17	588

*1 Diesel generator fuel oil consumption rate: 210 [g/kWh]
*2 CO2 reduction per fuel oil = 3 CO2 ton / ton
*3 Operation hours 2729h = 113.7 days

6. CONCLUSIONS

The sea trials demonstrated the durability of the Variable Phase Turbine and the Organic Triangle Cycle for marine applications. The system was insensitive to ship roll and pitch. Seamless startup and operation with the ship engine and electrical system were demonstrated. Substantial gains in performance for an optimized OTC system were identified. Widespread application to conversion of waste heat from the Main Engine can have a substantial reduction in CO_2 as well as fuel use to meet the ship electrical requirements. A study of application to existing and new ship engines is recommended.

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