New-Technology Shipboard System Converts Heat from Engine Jacket Water into Electrical Power

With fuel accounting for a very high percentage of a ship's daily operating cost, there is increasing demand for solutions to reduce fuel consumption, with an additional benefit of reducing emissions into the atmosphere. One promising technology is waste heat recovery. Calnetix Technologies, working in close cooperation with Mitsubishi Heavy Industries Marine Machinery and Engine Company (MHI-MME) has developed a system called Hydrocurrent™, which uses an Organic Rankine Cycle (ORC) heat transfer process and a patented turbo-generator power conversion system to convert thermal energy from heat in the engine's jacket water into mechanical power to generate electricity. It can produce up to 125 kW of electrical power from a temperature source as low as 80°C, saving up to 200 tons of bunker fuel and reducing carbon monoxide emissions by 18 tons per year by reducing the load on the ship's bunker-burning diesel generators.

The ORC technology is derived from similar systems developed by Calnetix for other industrial heat recovery applications. Over the past five years, Calnetix has deployed over 35 MW of capacity in land-based ORC installations around the world.

The Hydrocurrent™ system has been approved by Class NK and Lloyd's Register following extensive tests and inspections of the system's turbo-generator, electrical, piping, controls and ORC components. The tests were witnessed by class surveyors and conducted in Calnetix's manufacturing and test facilities in Cerritos, California. The final acceptance tests took place in March 2015.

This White Paper provides a detailed description of the system components and how they work, followed by a summary of test procedures and results.

Background

A typical general cargo ship requires approximately 1 MW of electrical power when underway. A modern LNG carrier may require power in excess of 12 MW. Ship electrical power is typically provided by a combination of main engine-driven generator(s) and auxiliary engine-driven generators. International maritime regulations require at least two generators as part of the ship's main electrical system. Additionally, at least one generator needs to be independent of the speed and rotation of the main propellers and decoupled from the associated shaft.

Additional power generation capability can always be achieved by adding more generators via main or auxiliary engine generators. However, this adds significant operating cost, as well as adding to existing engine pollution. A better solution is to utilize the waste heat generated by the engines, to power a heat recovery cycle. Already, heat from engine exhaust is used on many ships for steam generation. To date, however, it has been difficult to extract heat from lower-grade heat such as the engine coolant.

Hydrocurrent™ technology aims to remove this barrier and tap into the low-grade jacket water heat to generate additional electrical power without incurring any additional fuel usage.

Hydrocurrent™ is designed for use with ship engines ranging in size from 10 to 30 MW output with a range of engine jacket water temperatures of 80 to 95°C, and with sea water cooling ranging from 10 to 32°C. In the following sections an operating point of 85°C heat source at 209 m^3/hr and 27°C coolant water temperature is assumed throughout.

The Hydrocurrent™ system consists of three primary components:

- a closed-loop Organic Rankine Cycle (ORC) module
- an Integrated Power Module (IPM)
- an electrical cabinet

Organic Rankine Cycle

Hydrocurrent™ utilizes the ship's main engine jacket water and sea water to facilitate evaporation and condensation of an organic working fluid with a boiling point lower than that of water, flowing through a closed loop. See Figure 1.

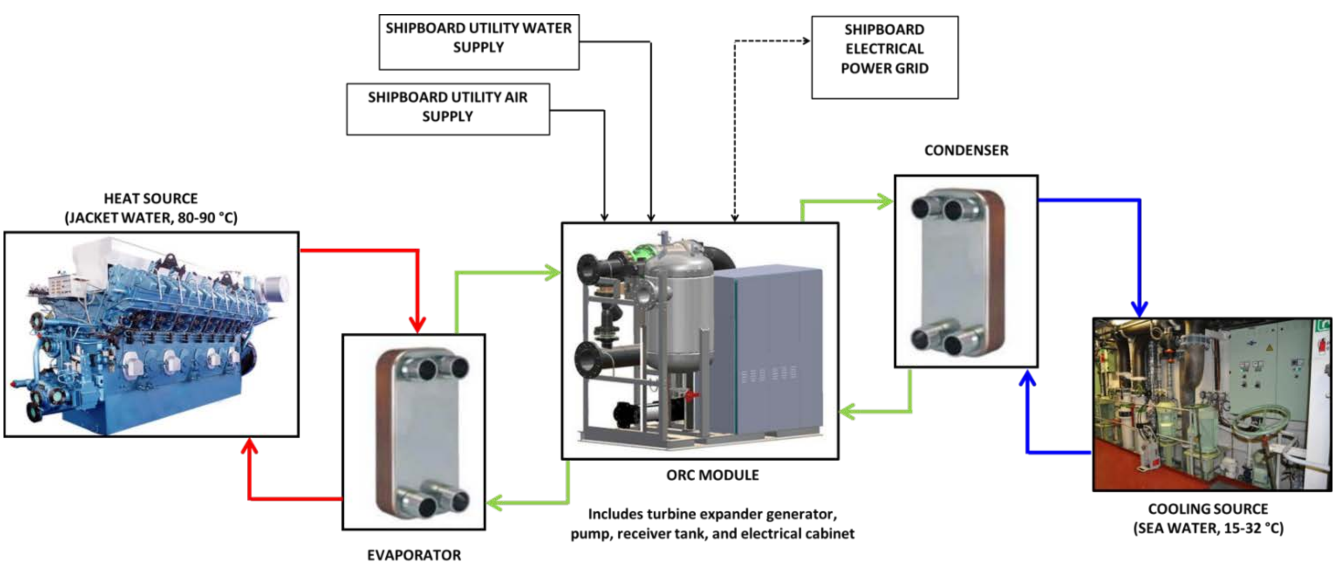

Figure 1. ORC system flow and ship interfaces.

The cycle begins with the liquid working fluid stored in a receiver tank at a pressure slightly above atmospheric and a temperature only a few degrees above sea water. The liquid is pumped to a higher pressure and circulated to an evaporator, where it vaporizes, absorbing heat from the engine jacket water. The pressurized vapor is then expanded through the IPM's turbine which produces electrical power with its integrated generator. The working fluid is then cooled to a liquid state in the condenser, rejecting heat into sea water which is pumped overboard. The liquid working fluid is finally returned to the receiver tank to repeat the cycle.

The working fluid pump is of centrifugal multistage design and is mounted horizontally to aid in achieving compactness of the skid. A special feature of the pump is its low suction head, which accommodates particularly cold condensing conditions encountered in colder oceans. Driven by a variable frequency drive, the pump is capable of varying the cycle flow and pressure to compensate for varying heat source conditions and desired power generation settings.

Electrical power produced in the IPM is converted to meet the power quality and specification requirements of the ship. This is accomplished in an active converter within the Hydrocurrent™ unit. The electrical output power automatically synchronizes with the ship's grid voltage and frequency and maintains this synchronization irrespective of ship grid fluctuation or heat source changes.

<u>Carefree™ Integrated Power Module</u>

The core of the Hydrocurrent™ system, the IPM, provides the means to convert pneumatic power into electrical power. The IPM is a combination of a radial turbine and a Permanent Magnet (PM) generator. A cross-section of the IPM is shown in Figure 2.

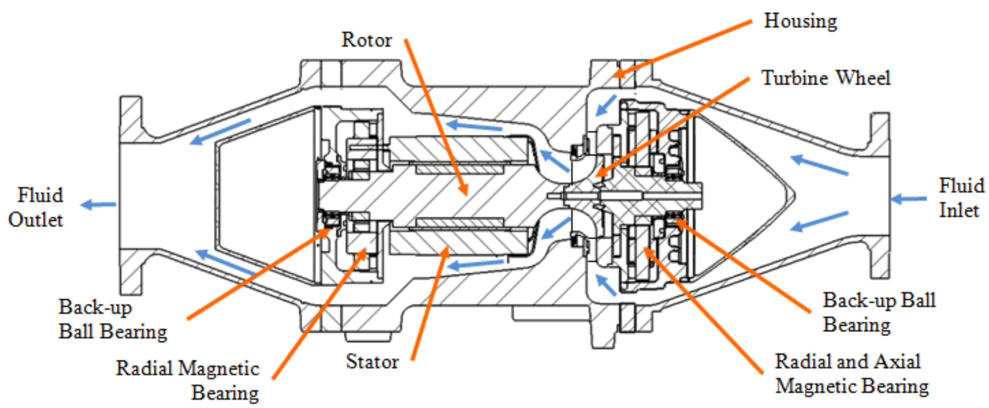

Figure 2. IPM cross-section.

The turbine and permanent magnets of the generator are integrated into a single rotor shaft and supported by active magnetic bearings. This fundamental design feature brings numerous advantages over typical turbo-generators:

1. The PM generator provides higher efficiency and smaller size over other types of generators.
2. Magnetic bearings enable frictionless operation eliminating energy loss, wear and maintenance associated with otherwise lubricated bearings.
3. The integrated turbine and PM rotor eliminates a coupling and penetration between a turbine casing and generator eliminating associated mechanical shaft losses and working fluid leakage potential.

4. The integrated generator immersed in the working fluid flow eliminates a need for an external generator cooling system which reduces system cost and maintenance significantly.

The turbine consists of a stationary nozzle and a radial wheel integrated into the rotor shaft. The turbine operates at an optimal speed of about 16,500 rpm at a rated terminal power of 137 kW. At the nominal pressure ratio of 3.0, the isentropic turbine efficiency (total to total) is about 90%. In addition, the turbine design accommodates off-design conditions with efficiency no less than 88.0% for pressure ratios ranging between 2.0 and 4.0.

The rotor is supported by five active magnetic bearings. The magnetic bearing design provides sufficient load capacity and load margin to ensure stable and robust operation under a variety of load sets. Sources of loading include the shaft weight, shaft unbalance, static offset (due to manufacturing variation), aerodynamic thrust and external vibration.

Electrical Cabinet

The multi-functional electrical cabinet has three primary sections:

- Power electronics
- Programmable logic and magnetic bearing controls
- Power distribution

The Power Electronics (PE) is a fully digitized motor controller with an active rectifier front end. It takes the variable, high-frequency power from the IPM generator and converts it to a regulated power that is synchronized to the ship's grid. Using Insulated Gate Bipolar Transistors (IGBT), the power of the IPM generator is converted from AC to DC. DC is then converted back to AC to match the grid voltage and frequency. The digital controls of the PE control the speed of the IPM as well as monitor the temperatures of the IGBTs and inductors. Speed and temperature limits are programmed within the firmware. Requiring minimal cooling water (less than 30 L/min), the PE delivers up to 125 kW of grid quality power at 440 VAC / 60 Hz or 380 VAC / 50 Hz with a conversion efficiency greater than 93% and a power factor 0.98 or greater. Total harmonic distortion (THD) of PE output power to the grid is no greater than 5% at 125 kW.

The Programmable Logic Controller (PLC) allows the ORC unit to operate autonomously. It monitors the temperatures and pressures necessary for proper operation as well as controls the automated engine jacket water and sea water source valves. Using temperature monitoring and the source valves the PLC ensures ship functions are unaffected when the ORC is offline. During operation, it also actively prevents the ORC from cooling the engine jacket water below 75^{o}C or heating the sea water above 32^{o}C in order to safeguard the operation of the ship's fresh water maker.

The Magnetic Bearing Controller (MBC) provides 5-axis control of the IPM's active magnetic bearings. The MBC continuously monitors the rotor orbits and currents. Under adverse conditions, such as high levels of unbalance or vibration, the MBC sends a message to the PLC, and the ORC system is shut down in a controlled and safe manner.

The Power Distribution Unit (PDU) is the point of interface to the ship's electrical power supply. This section contains the necessary circuit breakers, contactors, filters and fuses to distribute power to the ship's grid and ancillary ORC components.

Reliability and Maintainability

The Hydrocurrent™ system comprises a number of commercial off-the-shelf components (COTS), particularly in the electrical cabinet and power converter. The reliability of such components is governed by industry standards.

Since the IPM's generator uses the expanded working fluid as coolant, and the magnetic bearing system does not require any additional cooling, the entire IPM assembly is hermetically sealed. There are no rotating seals that require periodic maintenance. A hermetically sealed module together with non-wearing seals or bearings provides an inherently reliable, long lasting power module.

Factory Testing

Factory testing procedures are described below.

Several aspects of the ORC system are tested as individual components before the system assembly is completed. Further testing is done at the system level to ensure conformance to system level requirements. The IPM is comprised of the high-speed turbine expander together with the high-speed PM generator. The rotating assembly is supported on an active magnetic bearing system. Due to the complexity of this module and significance in determining the overall ORC system performance, a number of component level tests are conducted and validated against requirements.

The turbine expander magnetic bearing system is tested by levitating and spinning the IPM rotor independent of the overall ORC system. Using the MBC, the performance of the bearing system can be monitored and recorded. Furthermore, any changes to the compensator can be made at this time. Load capacity of the magnetic bearings is validated using a load cell, see Figure 3. The plot in Figure 4 shows the measured axial force aside the theoretical axial force of the magnetic bearing.

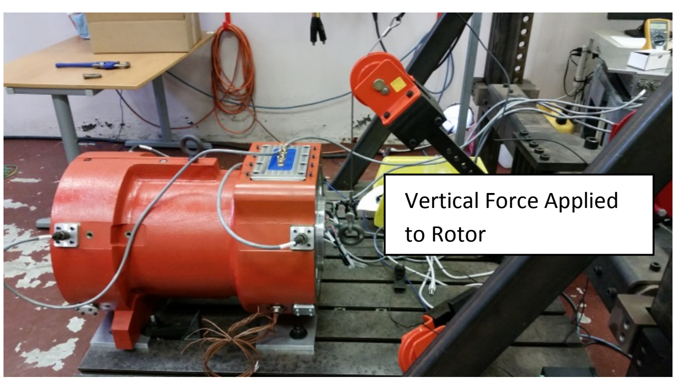

Figure 3. IPM under magnetic bearing load testing.

The PE is also tested independent of the ORC system, whereby the active rectifier and inverter are tested to maximum load capacity and temperatures at the heat sink are monitored and recorded. Once these subassemblies have been tested and validated, the ORC system assembly takes place.

Thereafter, the system is tested at the Calnetix ORC Test Facility, shown in Figure 4, with representative heat source and condensing conditions. To validate turbine performance, the ORC system is operated at conditions which replicate engine jacket water using a closed loop of high pressure hot water.

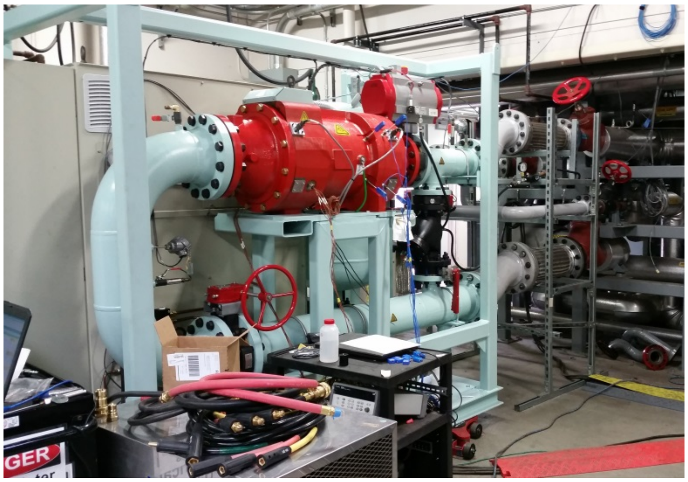

Figure 4. ORC under test at the Calnetix ORC Test Facility.

In testing, the ORC is operated at several PE power output levels (between 50 and 125 kW). The IPM is fitted with pressure and temperature transducers both before and after the turbine. In addition, condensing conditions are varied to change the turbine pressure ratio so as to generate a full map of turbine performance and efficiency data for validation against design analysis.

ORC and IPM performance are compared against design by measuring heat input from the hot water, working fluid flowrate, IPM turbine speed, IPM inlet and outlet conditions, generator and PE power outputs. From test measurements, the ORC gross efficiency is calculated as the quotient of PE power output to the rate of heat input from the hot water.

In the full power test, the cooling water temperature was maintained at 27^oC and the ORC was operated to the maximum PE power output of 125 kW. Test measurements reported in Table 1 are average conditions at steady state operation.

The total to total isentropic efficiency is very close to the design value and was calculated using the measured generator power output, IPM inlet pressure and temperature, and the wheel outlet pressure. Viscous rotor losses and generator efficiency correlations were used to arrive at the isentropic efficiency given these quantities were not measured directly. The system gross efficiency and IPM turbine isentropic efficiency are subject to a relative measurement uncertainty of less than 3%.

Table 1. Test vs. Design at PE Power Output of 125 kW.

Description	Design Prediction	Test Results
Working Fluid Flowrate	8.1 kg/s	8.5 kg/s
IPM Turbine Speed	16,500 rpm	16,500 rpm
IPM Inlet Temperature	80.3 C	79.1 C
IPM Inlet Pressure	6.9 bara	6.7 bara
Heat from Hot Water	1845.6 kW	1942.9 kW
Gross Efficiency	6.8%	6.5%
IPM Turbine Isentropic Efficiency (total to total)	90.3%	89.1%

Ship Trials

It is expected that ship trials will begin in the second half of 2015.

About Calnetix Technologies

Calnetix Technologies, LLC ("Calnetix"), headquartered in Cerritos, Calif., is focused on Innovation That Drives Industries™. The company specializes in high-performance, high-speed motor generators and best-in-class advanced magnetic bearings and control systems. Calnetix's patented underlying technologies, which have been in use since the company's inception in 1998, have made Calnetix a world leader in the design and production of high-speed machines. The company's overall technology portfolio and system integration capabilities have led to development and production contracts with industry leaders and the start of many successful subsidiaries that focus on unique niche markets. For more information, please visit www.calnetix.com.