WASTE HEAT UTILIZATION OF MAIN PROPULSION ENGINE JACKET WATER IN MARINE APPLICATION

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ABSTRACT

As world trade grows, fuel prices increase, and International Maritime Organization (IMO) emissions requirements tighten, there is more demand for the marine industry to employ innovative means of reducing the fuel consumption and emissions of shipping vessels.

The main propulsion engines of large shipping vessels produce great quantities of jacket water heat at temperatures below 95 °C, but this valuable heat energy is transferred to cooling systems and rejected to the world’s oceans as waste. At the same time, the electrical needs of these vessels are sustained by burning diesel fuel to run generators. To utilize the jacket water waste heat Calnetix Technologies, in partnership with Mitsubishi Heavy Industries (MHI), has developed the Hydrocurrent™ 125EJW (Engine Jacket Water) Organic Rankine Cycle (ORC) to convert low-grade heat energy into grid-quality electric power.

Large vessels such as tankers, bulk carriers, and container vessels with an engine output of approximately 30 MW can output as much as 300 m^3/hr of 80 to 95 °C jacket water from their main propulsion engines. When integrated into the jacket water and sea water systems of such vessels, the ORC unit can produce up to 125 kW of gross grid-quality electric power. To produce 125 kW of power, a diesel generator would consume as much as 250 metric tons of diesel fuel per year in addition to its generated emissions and maintenance requirements.

Calnetix Technologies has leveraged its core technologies to develop a new high efficiency ORC system that is compact and modular in design. In addition, the ORC unit has been certified by marine classification societies Nippon Kaiji Kyokai (NK) and Lloyd’s Register (LR) for installation on any vessel without modification. The following is a description and validation of the commercially available, class society certified system that has been realized.

1. INTRODUCTION

A typical general cargo ship requires approximately 1 MW of electrical power whereas a modern Liquid Natural Gas (LNG) carrier may require power in excess of 12 MW. Ship electrical power is typically provided by a combination of main engine driven generators and auxiliary engine driven generators. International maritime regulations (International Convention for the Safety of Life at Sea (SOLAS), 1974) 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.

The number of auxiliary engines and utilization of them versus the main engine is a subject of trade studies at vessel design and thereafter managed by Marine Fuel Management (MFM). The MFM has the primary goal of reducing fuel usage. This is achieved by various means including route planning and throttle management. As well as reducing fuel consumption, considerations need to be given to other aspects of fuel usage at sea in order to comply with ever stiffening international marine pollution regulations like MARPOL 73/78 (Rizzuto and Soares, 2012).

By augmenting existing electrical power generating capability of ships, a more flexible and ultimately better optimized fuel management case can be constructed whereby the primary goal of fuel consumption as well as electrical power availability and pollution reduction goals can be attained. 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 (Ichiki et al., 2011). To date, low-grade heat such as engine coolant (jacket water) has been difficult to utilize. A review of literature existing on the subject of applying ORC technology to utilize the low-grade waste heat of marine diesel engines yields analytical research, but none affirming any real life application (Yu et al., 2013) (Yang and Yeh, 2015) (Song et al., 2015) (Soffiato et al., 2015) (Jin et al., 2012). The following describes a unique and commercially viable solution which 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 or added emissions. The subject being beyond investigation of a proposed system, the ORC system described has been fully tested and certified for use on any vessel.

2. HYDROCURRENT^{TM} 125EJW ORC

As shown in Figure 1, the heat source, in the form of jacket water, is supplied from the engine at temperatures between 80 and 95 °C. This heat is transferred to the ORC's organic working fluid (R245fa) via a heat exchanger. Since the heat exchanger is used to elevate the temperature of the working fluid as well as turn the fluid into vapor, it is often referred to as the evaporator. A similar heat exchanger is used to condense the working fluid after expansion; this is referred to as the condenser. The coolant to turn the expanded fluid into liquid is supplied via readily available sea water.

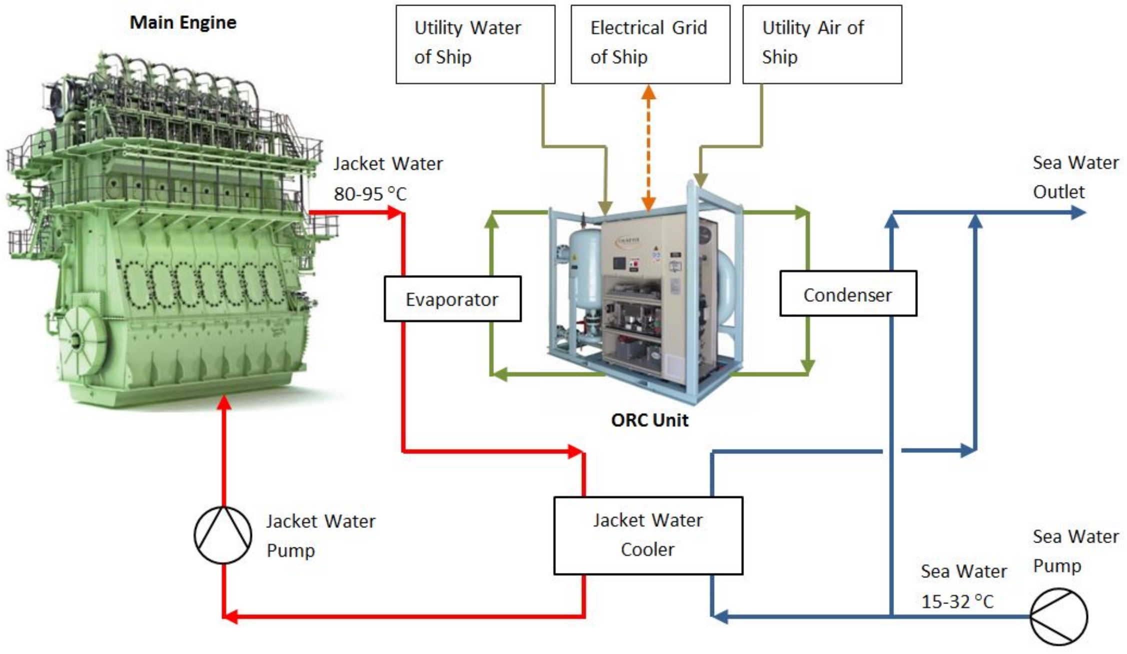

Figure 1: ORC system flow and ship interfaces. The engine pictured is a graphical rendering of a MAN G-type engine obtained from DIESELFACTS issue 1/2013 p. 5.

After the working fluid has been pressurized and evaporated it enters the Carefree Integrated Power Module^{TM} (IPM). The high speed (16,500 rpm) turbine expander and permanent magnet generator are integrated into a single shaft within the IPM and this rotating assembly is supported by an active magnetic bearing system. The high speed generator converts the pneumatic power, developed from the working fluid, into electrical power. Electrical power from the generator requires conversion to meet the power quality and specification requirements of the ship. The conversion takes place in an active converter within the ORC 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.

Since the electrical power output of the ORC system is dependent on engine jacket water heat availability, the system is available whenever the main engine is in operation. By changing the power set point at the ORC unit, the power output can be modulated to meet the changing electrical load needs. This unique approach not only furnishes additional electrical power that can be readily modulated but it does so without increasing the ship’s fuel consumption or pollution.

2.1 ORC Development

The ORC system as a whole utilizes the ship's main engine jacket water and sea water to facilitate evaporation and condensation of the organic working fluid in order to produce grid-quality electric power. At the design condition (125 kW gross power output), the ORC requires 208.6 m^3/hr of 85 °C engine jacket water along with 341 m^3/hr of 27 °C sea water. Figure 2 depicts the process flow diagram at the design condition.

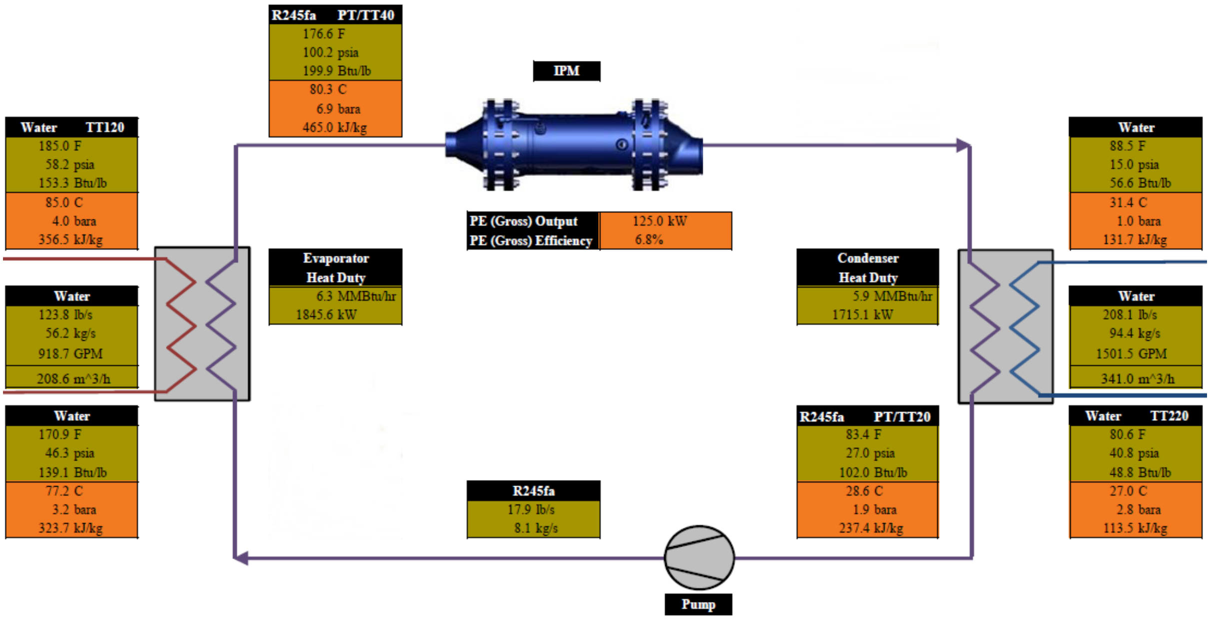

Figure 2: ORC process flow diagram at the design condition

The cycle begins with liquid working fluid stored in a receiver tank at temperature only a few degrees above that of sea water. The liquid is pumped to a higher pressure and circulated to an evaporator to absorb 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 by the condenser utilizing cooling available from the ship's sea water system. The liquid is finally returned to the receiver tank to repeat the cycle.

Some key design features sought in the development of the ORC unit were: 1) Compact design for ease of integration into a new or existing ship engine, 2) Robust and reliable system requiring minimal maintenance, 3) Passive auxiliary system that does not interfere with normal ship functions. Design efforts focusing on the most significant components of the ORC unit were important to the outcome of the development. Details of the function and analysis of the following ORC components will be discussed: 1) IPM - turbine and power generator, 2) Electrical Cabinet - power electronics, controls, and distribution, 3) Working Fluid Pump. Selection of the rotor-bearing system, working fluid pump and other components is based on extensive field evaluations on other Calnetix ORC systems.

2.2 Carefree Integrated Power Module™

The core of the ORC unit, 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 along with overall dimensions and general materials of construction are shown in Figure 3. The alloy steel turbine and samarium-cobalt 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.

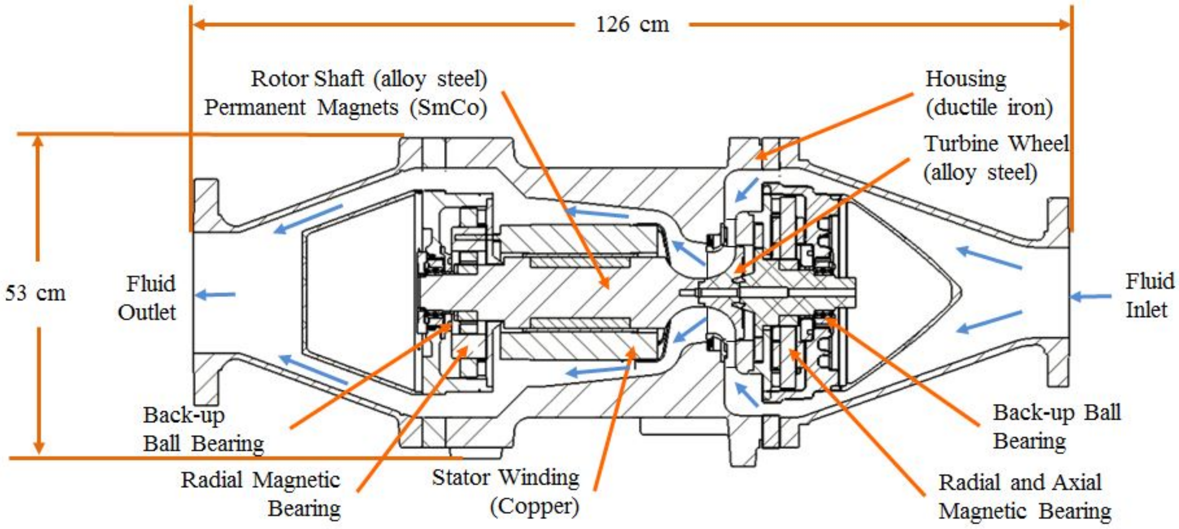

Figure 3: IPM cross-section

Design of the turbine is developed through an iterative process. Initially a mean-line analysis is carried out where size and speeds of the turbine are determined using efficiency speed maps. Thereafter, the performance of the turbine is characterized over a wide range of operating conditions. Additionally, the downstream aerodynamic losses are calculated and the entire IPM assembly is updated using a process simulation tool (Mirmobin and Sellers, 2015). Once an optimal operating point has been determined, detailed 3-D aerodynamic analysis is carried out. Any changes to the design are made at this time after which final designs of the turbine, wheel and diffusers are completed.

The turbine consists of a stationary nozzle and a shrouded radial wheel integrated with the rotor shaft. At nominal inlet conditions (6.9 bara and 80.3 °C), 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% and the specific speed is 0.82. To accommodate jacket water source temperature variation, the ORC control system maintains the level of superheat at the inlet to the IPM by modulating the working fluid pump speed and heat source valve position.

Therefore, there is little to no effect on vapor quality and subsequent turbine efficiency as the jacket water temperature varies.

The rotor is supported by five active magnetic bearings; one grouping is a combination radial-axial set like that of McMullen et al. (2000). 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. Selection of magnetic bearings was based on extensive use and field data from other Calnetix systems. Although conventional bearings could be used in this case, additional design considerations would need to be taken into account to ensure the bearings remain lubricated (cooled) whilst the coolant does not migrate into the working fluid and contaminate the system.

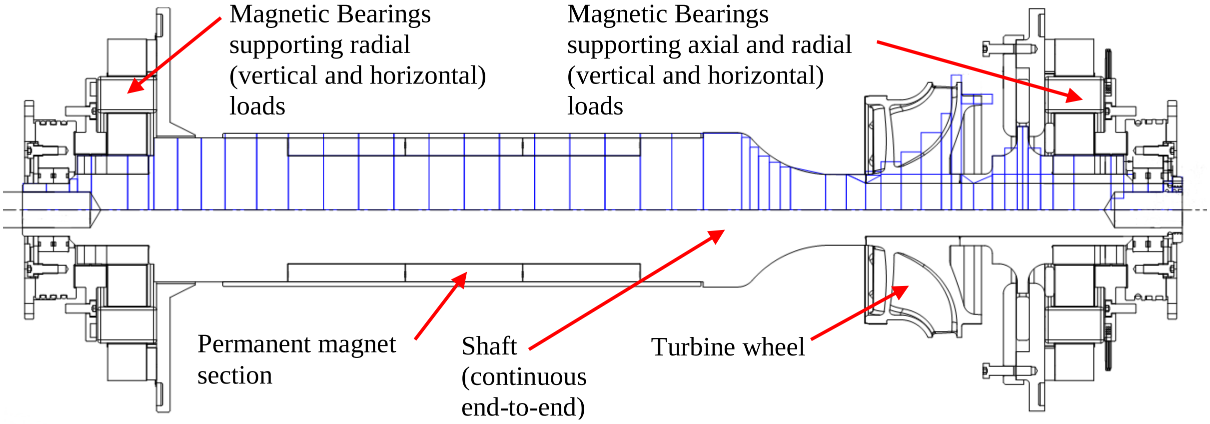

Figure 4: Rotordynamic model of IPM rotor

A rotordynamic model, shown in Figure 4, was constructed for dynamic modeling to identify natural frequencies and aid in magnetic bearing design and controls development. The rotordynamic model accounts for all mass and stiffness of the structure and couplings in between. Natural frequency of the rotor assembly is validated using a free-free resonance test. Free-free natural frequencies are determined by measuring excitation response of accelerometers affixed to rotor nodes of interest.

The magnetic bearing forces are calculated using a finite element analysis of the magnetic paths around the actuator. Permanent magnets provide a bias flux for the magnetic bearings which simplifies control with linear control response to control current commands, and when the rotor position is offset from the center can reduce the current required to maintain rotor levitation during operation; the low current consumption translates into a total IPM magnetic bearing power consumption of only about 200 W. Once the magnetic bearing design has been developed, the response of the magnetic bearing system (sensor, actuator and compensator) is modeled. The bearing design is validated with testing whereby forces exerted by the bearing system are measured for given displacements of the rotor.

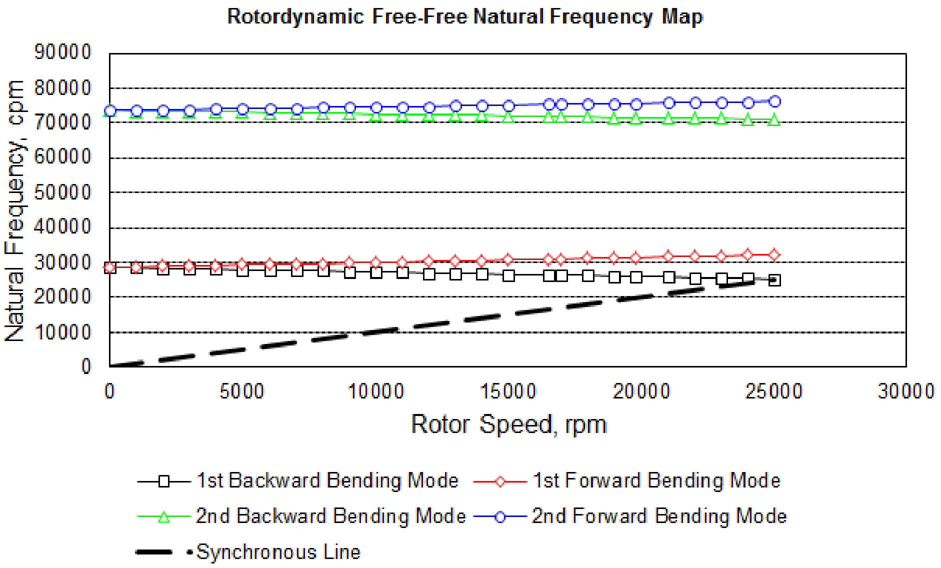

Figure 5: Free-free natural frequency map of IPM rotor

To ensure stable operation it is important to identify the natural frequencies of the rotor within the range of operating speeds, including overspeed. The overspeed limit required by marine classification societies NK and LR is 120% of the rated speed, in this case 19,800 rpm. Figure 5 depicts the free-free rotordynamic frequency map. In good practice a 15% design margin is sought between the first bending mode and the overspeed. Findings are that the first bending mode is excited at about 25,000 rpm which is well over 15% of overspeed.

2.3 Electrical Cabinet

The ORC unit is fitted with a multi-functional electrical cabinet with three primary sections: 1) Power Electronics, 2) Programmable Logic and Magnetic Bearing Controls, 3) Power Distribution.

The Power Electronics (PE) is a fully digitized motor controller with an active rectifier front end. The variable high-frequency power from the IPM generator is converted to 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 power is then converted back to AC at 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 0.99 or greater. Total harmonic distortion (THD) of 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 unit is offline. During operation, it actively prevents the ORC unit from cooling the engine jacket water below 75 °C or heating the sea water above 32 °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 shutdown 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 the generated power to the ship’s grid. The PDU also provides grid power to the magnetic bearings, working fluid pump and other auxiliary loads within the ORC unit.

2.4 Working Fluid Pump

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. The pump's motor is 3-phase, 2-pole and is rated for 7.5 kW. Driven by a variable frequency drive, the pump is capable of varying the working fluid flow and pressure to compensate for varying heat source conditions and desired power generation settings.

2.5 Reliability and Maintainability

The ORC unit 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 bearings provides an inherently reliable, long lasting power module.

3. ORC TESTING

Testing and validation of the ORC unit is primarily done in two phases - factory testing and sea trials. The following discussion addresses factory testing, sea trails are a subset of such tests conducted at sea for further validation of the design in actual operating environment.

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.

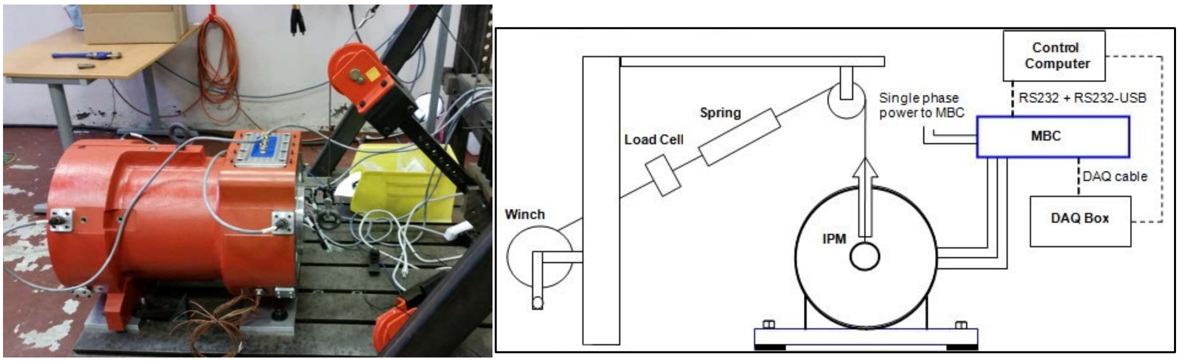

Figure 6: IPM under magnetic bearing load testing (left); IPM magnetic bearing load test setup (right)

Load capacity of the IPM magnetic bearings is validated using a load cell and MBC setup shown by Figure 6. The IPM magnetic bearing system is then tested by levitating and spinning the rotor independent of the overall ORC system. Using the MBC, the performance of the bearing system can be monitored and recorded for evaluation.

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 7, 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.

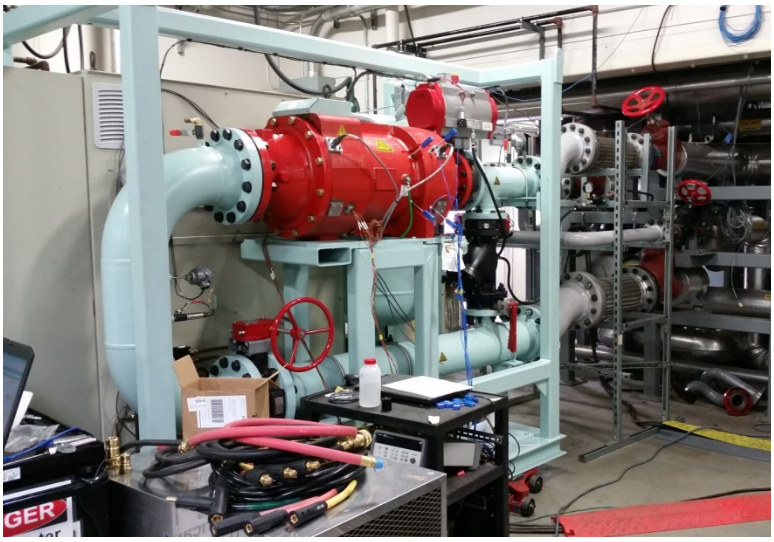

Figure 7: ORC under test at the Calnetix ORC Test Facility

In testing, the ORC unit 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.

The Gross Efficiency and Net Efficiency of the ORC are defined by equations (1) and (2). Equation (3) defines the Net Power Output of the ORC where the Parasitic Load includes the power of the working fluid pump, IPM magnetic bearings, and all other electrical loads within the ORC unit.

$$Gross\ Efficiency = \frac{PE\ Power\ Output}{Rate\ of\ Heat\ Input} \tag{1}$$

$$Net\ Efficiency = \frac{Net\ Power\ Output}{Rate\ of\ Heat\ Input} \tag{2}$$

$$Net\ Power\ Output\ =\ PE\ Power\ Output - Parasitic\ Load \tag{3}$$

The ORC and IPM turbine efficiencies are compared against design by measuring the rate of heat input from the hot water source, working fluid flowrate, IPM inlet and outlet conditions, PE and Net power outputs. The total to total isentropic efficiency was calculated using the measured generator power output, IPM inlet pressure and temperature, and the wheel outlet pressure. Viscous rotor losses and generator efficiency were not measured, so design correlations for these quantities were used in the calculation of the isentropic efficiency. In the full power test, the cooling water temperature was maintained at 27 °C and the ORC unit was operated to the maximum PE power output of 125 kW with an IPM speed of 16,500 rpm. Test measurements reported in Table 1 are average conditions measured while at steady state operation. The relative measurement uncertainty is the combined uncertainty of both the standard deviation of the measurement set and the inherent uncertainty of the calibrated instrumentation and fluid property calculations.

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

Description	**Design Prediction**	**Test Measurement**	**Relative Measurement Uncertainty**
Working Fluid Flowrate	8.1 kg/s	8.5 kg/s	0.50 %
IPM Inlet Temperature	80.3 °C	79.1 °C	0.95 %
IPM Inlet Pressure	6.9 bara	6.7 bara	0.28 %
PE Power Output	125.0 kW	125.3 kW	1.03 %
Net Power Output	119.1 kW	119.8 kW	1.03 %
Rate of Heat Input from Hot Water Source	1845.6 kW	1942.9 kW	2.21 %
Gross Efficiency	6.8 %	6.5 %	2.43 %
Net Efficiency	6.5 %	6.2 %	2.43 %
IPM Turbine Isentropic Efficiency (total to total)	90 %	89 %	2.43 %

4. CONCLUSIONS

In this paper the need to develop a heat recovery system utilizing low grade heat from ship engine jacket water has been outlined. Such a need arises to address the ever increasing electrical power demands of modern ships whilst reducing overall pollution emanating from power generating sources.

To achieve this goal, development of a novel low-grade heat source ORC system has been described. The ORC system not only achieves the primary goal of electric power generation without additional fuel consumption, it also adds to overall electrical power availability and adds a dimension to overall electrical system flexibility.

Performance test results have been provided and analyses of key performance metrics have been discussed. Much of the discussion in this paper has been focused at marine application of such architecture. It should be noted, with the abundance of low-grade heat sources, such as low-temperature geothermal, the same architecture, using the same ORC system, can be employed in many other low-grade heat recovery applications.

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