THE BENEFITS OF SHIP WASTE HEAT RECOVERY USING A SUPERCRITICAL ORGANIC RANKINE CYCLE

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ABSTRACT

The energy contained within the exhaust gases of ship engines offers a good potential source for useful energy using waste heat recovery. Organic Rankine Cycles (ORC) are a relatively new but proven technology, but remain little used on ships (beyond some limited trials) as it appears ship owners have not yet been convinced on their benefits.

A recently developed supercritical version of the ORC called ScORC GRANEX®, has many desirable features for marine application. Compared to a steam Rankine cycle it requires less heat exchanger surface area and has greater thermodynamic efficiency delivering more useful power. This leads to a more compact system that can be more easily retrofitted with a reduced payback term. This paper presents the performance features of the GRANEX® technology and examines the conceptual installation on a military vessel, showing the size and weight of equipment and how it can be installed. Based upon the engine exhaust data at specific loadings, the recovered electrical energy is identified to determine the fuel saved, the emissions reduced and the increased range of a transit. Equipment and installation costs are estimated and the calculation of predicted fuel savings on typical ship operations determines the likely return of investment. A careful consideration of the maintenance of the technology is included, which highlights the state-of-the-art equipment developed towards minimal maintenance.

Keywords: Super-Critical Organic Rankine Cycle, Waste Heat Recovery

1. INTRODUCTION

Organic Rankine cycle (ORC) sets are used on land-based applications such as waste gas heat rejection from Gas-fuelled Generator sets at landfill sites and as part of Combined Heat and Power (CHP) systems. To date there has been a limited uptake onboard ship due to the lack of products which are marketed and which are certified to meet classification society requirements. There is also a lack of a defined commercial approach to achieving an installation which has a robust commercial footing. This study seeks to show that ORC have a useful role to play in achieving useful fuel efficiency benefits once they have overcome Class requirements.

There have been many recent articles and technical papers on ORC and in recent years Enertime and OpCon Marine (2012) have claimed to have successfully trialled an ORC system on a marine engine. A few key documents which have influenced our work are reviewed below.

Panesar's thesis (2012) provided a good summary of the current state of ORC and provides a good source of typical system operating parameters. The parametric operating assumptions at full load from Panesar and from other sources are shown in **Error! Reference source not found.** together with the values used in this study.

Auld (2013) describes the use of sub-critical ORC with three different waste heat sources one of which is the waste heat from an engine. The analysis uses a direct exhaust heat transfer from exhaust gas to the refrigerant. The paper provides an insight into the optimisation of an ORC cycle, something which this model is not intended to do due to its general applicability for a range of engines. Auld makes reference to the Super Truck programme sponsored by the US DOE (Koeberlein, 2011) which sought to reduce fuel consumption by 10%. The program uses the Cummins ORC system but there is limited information available in public on its use.

Katsanos (2010) has also studied the use of ORC on trucks and using some generous assumptions and R245fa as the working fluid (wf), he achieves an overall fuel reduction of 8 to 10% when used with Exhaust Gas Recirculation (EGR).

Moghtaderi and Doroodchi (2009) made a case for the adoption of a Supercritical Organic Rankine cycle (SORC) so that the wf temperature is closer to that of the heat source and thus there is better use of the available heat. Due to the typical proximity of the lines of constant pressure in the Turbine Inlet Pressure (TIP) region the turbine exit stream may have a higher energy content than a conventional ORC. For this reason the SRC is employed with a recuperator to provide a better yield for the fluid heater heat and to reduce the heat lost through the condenser. The recuperator improves the net yield per unit enthalpy change.

It is the application of SORC technology that is presented in this paper. Granite Power Limited (GPL) of Sydney, Australia supply SORC systems which generate useful power from a wide range of heat sources. BMT have worked with GPL to model their equipment onboard an example ship to demonstrate the utility of a SORC system.

2. OBJECTIVE

The objective of these studies is to identify the fuel consumption savings achieved through the application of SORC on the HMAS Canberra. As an all-electric ship with both GT and Diesel gensets the Canberra is a good case where the SORC can make a useful contribution to the Ships Electrical Load (SEL) which also raises the total effective power generating capacity.

This will be achieved using a steady-state SORC model analysis which is robust and accurate enough to allow the benefits and operating issues of an ORC system to be identified with confidence.

The SORC is driven by the heat recovery from the exhaust gas of the gas turbine (GT) engine and the diesel engines (DE). The model is to allow the electrical output power to be determined which supplies the demand due to the SEL and which supplements the power supply from the gensets themselves.

3. DESCRIPTION

A conventional Rankine cycle comprises a boiler which heats water into steam. The steam drives a turbine which then drives a load such as a propeller or a generator. The vapour exiting the turbine is cooled by a condenser which is usually water or air cooled so that the vapour is condensed to water. The water collects in a well from whence it is pumped to the boiler by the feed pump and the cycle starts over again.

In an SORC system the water is replaced with a refrigerant wf which is comprised of a carbon-based molecule. This allows the fluid to evaporate at temperatures below 100°C and thus can be used for the recovery of useful work from so-called "low-grade" sources of heat and often results in a more compact solution. At higher grade sources temperatures, like that of a GT exhaust, SORC seldom achieves an efficiency comparable to the steam Rankine cycle. However it is more compact with a much reduced operator and support burden: on a land-based system, the operating and maintenance cost of a generic ORC system is expected to be 25% of a comparable steam system depending the on the working fluids used and the condensing loop design (Beleznay, P et al., 2015).

4. SPECIFICATION

4.1 SCOPE

The model developed to represent an SORC system is based on a pragmatic design which is robust enough to identify the benefits across the load range with a wide range of heat and temperatures sources using a standard sea water temperature indicative of North European waters.

4.2 HEAT SOURCE

In this case study, the exhaust gas heats the R134a refrigerant directly in a heat collector placed in the engines' exhaust gas streams. The assumed funnel temperature above 120°C is high enough for operations with fuel of 0.1% sulphur to avoid the risk of sulphuric acid condensing and causing corrosion. In order to vary the heat load to the fluid heater, the wf flow to the fluid heater is varied at a constant temperature, this ensures that the SORC system operates at (or near) its thermodynamic design point.

4.3 WORKING FLUID

The wf of a SORC system is to be affordable with an acceptable Global Warming Potential (GWP). The GPL supplied system is designed as a gas-tight system with minimal leakage. The wf is to ideally have low toxicity and low flammability.

A refrigerant with a positive (i.e. also known as a drying fluid) or infinite (i.e. isentropic) saturated vapour curve is also desirable so that the gas does not condense into a liquid at the turbine exit as droplet impact can lead to damage to the turbine blades.

The refrigerant chosen as the wf for these studies is R134a: it is non-flammable which allows it to be used in ships' machinery spaces and is a commonly available refrigerant which is commonly found in ship's provision plants. In summary R134a represents the right balance to a number of selection issues. Although it has a high GWP its high availability and proven use makes it a good candidate for the basis of these studies.

4.4 CONDENSING FLUID

For this study the heat sink is sea water which is the standard cooling medium onboard ship. The temperature of the sea water (Tsw) to the condenser is 10.0°C based on the annual average sea water temperature around Northern European waters (UK Defra Data Sources).

4.5 PHYSICAL MODELS

A simple ORC system comprises a feed pump, a fluid heater, an expander (i.e. a turbine) and a condenser. Such an ORC system passes 80% or so of the fluid heater heat to the heat sink and only 20% or less is used by the turbine. To recover some of this heat and render the ORC a more efficient system, a recuperator is introduced. A SORC requires such a recuperator to allow the specific power per unit enthalpy change to be augmented through re-use of the input heat. A recuperator is located after the turbine to collect and reuse heat in the exhaust vapour to heat the feed into the fluid heater as shown in Figure 1.

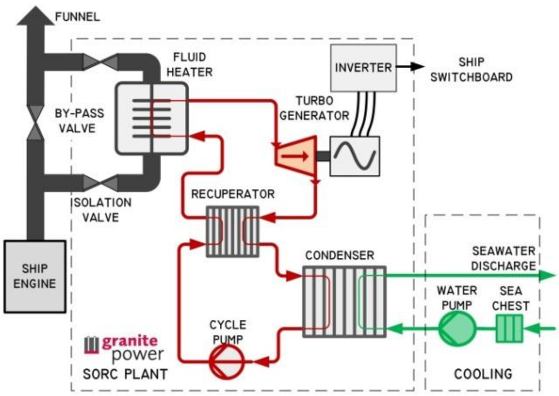

Figure 1 – SORC Schematic

Waste heat recovery (WHR) heat exchangers acting as fluid heaters are located in both the diesel and GT engine exhaust streams to heat the refrigerant directly. The flow of the refrigerant is regulated which together with a suitable heat exchanger design and other cycle conditions will ensure the refrigerant does not become exposed to temperatures that may lead to its being degraded or even decomposed. An exhaust gas diversion arrangement and a facility to a bypass exhaust gas round the heat exchanger is provided so that any excess heat (particularly from the LM2500) can be diverted safely, and to safeguard the WHR plant should it fault.

The SORC system operates in a way which can be predicted through the use of Main Physical Parameters (MPP) that are the key fixed design points:

- 1. Condenser exit
- 2. Cycle pump outlet
- 3. Recuperator liquid exit
- 4. Fluid heater exit
- 5. Expander exit;
- 6. Recuperator vapour exit.

The ORC system operates so as to keep the MPP at their design points, specifically at the expander inlet by varying the mass flow of the wf. In this way the physical state of the wf is kept sensibly at its design parameters at each point around the circuit which is best for a predictable control and the best overall efficiency.

Thus with changing exhaust gas conditions, the wf mass flow is varied to ensure a constant supply temperature and pressure at the inlet to the expander (point 4). Therefore, the heat into the ORC and the power it can generate varies with the exhaust gas temperature and the mass flow of the heat source.

The sea water coolant flow rate to the condenser is varied to achieve the wf design point conditions at the condenser exit, Point 1.

4.6 ASSUMPTIONS

To allow a useful model to be presented here, certain assumptions and simplifications have been made and they are identified below:

- The SORC system regulates the flow of the wf so that the input temperature to the expander is constant and thus its specific heat capacity is constant;
- The fluid heater model includes the functional and physical behaviours in the heat exchanger;
- The flow in the heat exchangers is counter-current flow. The overall heat transfer coefficient for the fluid heater and condenser is kept constant;
- The pressure drop of the heat source liquid, the wf and the sea water across the condenser, the fluid heater and the recuperator varies with the square of the flow;
- The pinch point temperature difference for all the heat exchangers is constant;
- The losses in the kinetic and potential energy of the internal and external fluid streams are considered negligible;
- Heat transfer between the ambient environment and the heat exchangers is neglected;
- The efficiency of the pump and turbine are supplied by equipment vendors and are assumed to be constant across the load range.
- The wf exits the condenser as saturated liquid ($x = 0$).
- In this case the engine's performance is not affected by the additional pressure-drop over the exhaust gas heat collector.
- The exhaust gas temperature leaving the heat recovery device is to be at or above 120°C if the fuel is 0.1% S MDO equivalent. This avoids the condensation of sulphuric acid which can damage the exhaust trunking and destroy/reduce the life of the fluid heater.
- The R134a wf physical properties such as pressure, temperature, enthalpy, entropy and the vapour fraction are derived using a proprietary software package and other proprietary data held by GPL
- The same refrigerant is used for both the GT and the DE ORC systems.

The parametric assumptions are summarised in Table 1.

Table 1 - SORC Principal Parameters

Parameter	Value
Heat source supply temperature	260 °C
Heat source return temperature	136°C
Pump efficiency	70%
Turbine /expander efficiency	85%
Generator efficiency including inverter losses	92%
Pinch point temperature	5.0°C
Condenser pressure drop	0.035 bar
Fluid heater pressure drops:	
Exhaust gas	0.075 bar
Working fluid	1.0 bar
Cooling water temperature rise in condenser	4.0°C

4.7 STUDY VARIABLES

Those variables which the control system seeks to keep sensibly constant across the load range were varied to allow the robustness of the system to be assessed. Specifically:

a. The diesel engines operate at 40% or above with an exhaust gas temperature which falls with increasing load as the engine's efficiency increases. The minimum exhaust gas temperature is 297°C so the heat source temperature at the DE expander inlet was set to 260°C which is believed to avoid the risk of wf degradation with a reasonable margin.
b. The GT engine operates at 50% load and above with an exhaust gas temperature of over 550°C. Therefore the heat source temperature at the GT expander inlet was also set to 260°C.

4.8 EQUIPMENT SPECIFICATION

Table 2 provides a summary specification of the equipment used in the SORC for each engine type.

Table 2. Summary of SORC Principal Operating Parameters

Parameter	Value
Ambient air temperature	15°C
Sea water temperature	10°C
Expander inlet temperature	260°C
Expander inlet pressure	80 bar
DE ORC rating	857 kWe
DE ORC efficiency	14.75%
GT ORC rating	7015 kWe
GT ORC efficiency	17.8%

4.9 TURBO-GENERATOR EXPANDER

Figure 2 shows the cross-section layout of the turbo-generator expander.

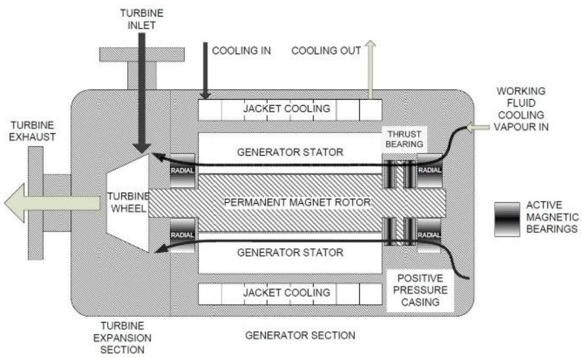

Figure 2. Cross-section layout of the turbo-generator expander

The turbine-generator design traditionally found for steam systems consists of a multistage expander, coupled through a reduction gearbox to a generator. The gearbox is required to reduce the high speed of the turbine to the standard 3600 rpm generator to deliver 60 Hz. The arrangement requires a mechanical seal system to minimize the leakage of working fluid through the turbine shaft. The gearbox and bearings of this design require lube oil conditioning.

Development of high speed motors and magnetic bearings in the air-conditioning industry have led to modern ORC turbo-generators as shown in Figure 2. The high speed generator can be directly coupled to the generator to avoid the need for a reduction gearbox. Oil lubricated bearings are also eliminated by introducing active magnetic bearings which create a very low friction non-contact support of the high speed turbine and generator shaft. Since there is no chance of oil contamination in this design, the actual working fluid can be used as a cooling vapour internal to the generator. Introducing this fluid into the generator casing at a slightly higher pressure than the turbine outlet pressure ensures cooling flow by allowing the vapour to pass into the turbine discharge. This feature eliminates the need for a mechanical seal and the complete package becomes semi-hermetic in which there is almost zero chance of fluid leak, and requires no bearing or oil conditioning maintenance. The high speed generator operates over five times the speed of a traditional generator and is considerably smaller than an equivalent standard speed generator. This advance in turbine-generator design means modern ORC design can have a much smaller installation package when compared to traditional steam WHRS.

5. SORC PERFORMANCE

5.1 HEAT COLLECTOR

The pressure drop over the heat collector is assumed to be 0.75kPa at the operating design point (i.e. full engine exhaust flow). This has a very small impact on the exhaust back pressure and there is no modification to the engine rating.

5.2 SORC RESULTS

Results are provided for the application of the SORC to the MAN DE. The SORC model has generated performance data for the range of wf mass flow from 0 to the full flow of 13kg/s. Figure 3 shows the temperature (y-axis) versus entropy (x-axis) diagram based on data from REFPROP (Lemmon et al., 2013).

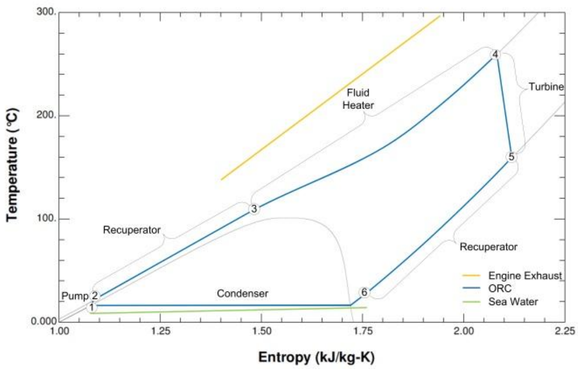

Figure 3 - SORC: Temperature-Entropy Diagram

Figure 3 shows the engine exhaust in yellow and the sea water temperature in green. The SW supply is 10°C with the condenser exit, point 6, set to 14°C.

The recuperator heat transfer is shown by the temperature changes between points 2 and 3 for liquid heating and points 5 and 6 for vapour cooling. The temperature changes are not equal even though the mass flows are the same through each side of the recuperator due to the differences in the enthalpy changes, i.e. the wf specific heat capacity is not constant with changes in pressure and temperature.

The fluid heater heat is added between points 3 and 4 and this allows the liquid R134a at point 2 to become supercritical at point 4 without passing through the unsaturated state.

The temperature drop across the turbine is shown between points 4 and 5. Post-turbine at point 5, the entropy has increased due to the non-ideal isentropic expansion. The exergy destruction is a function of the ambient temperature, the wf mass flow and the entropy difference.

Between points 6 and 1 the wf goes through a condensing process which is virtually isobaric.

5.3 INTERPRETATION

The results show that the SORC has much potential for achieving system efficiencies of over 15%, depending on the sea water temperature and the condition of the wf.

Although the exhaust gas temperatures fall with lower ambient air temperatures, the SORC efficiency improves with lower sea water temperatures. This is mostly due to the larger range of heat source and heat sink temperatures and hence the improved Carnot efficiency. For the reference SW temperature, the DE SORC efficiency is 17%.

6. SHIPS SPECIFICATION

The study considers the application of SORC to the HMAS Canberra as this ship has both GT and DE prime movers all driving alternators. A summary of the assumed ship's main particulars are shown in Table 3.

Table 3. Ships Main Particulars

Parameter	Value
Length	230m
Beam	32m
Draught (transit)	7.2m
Maximum contracted speed	20 knots
Endurance	9,000nm at 15 knots
Displacement	27,831 tonnes
DE gensets	2 x 7,448kWb
GT genset	1 in number 20,531kWb

Figure 4 shows the assumed ship-speed operating profile as the percentage engine loading (for each engine) on the y-axis versus ship speed (knots) on the x-axis. The assumed ship's electrical load, i.e. non-propulsion, is assumed to be 3,266KWe.

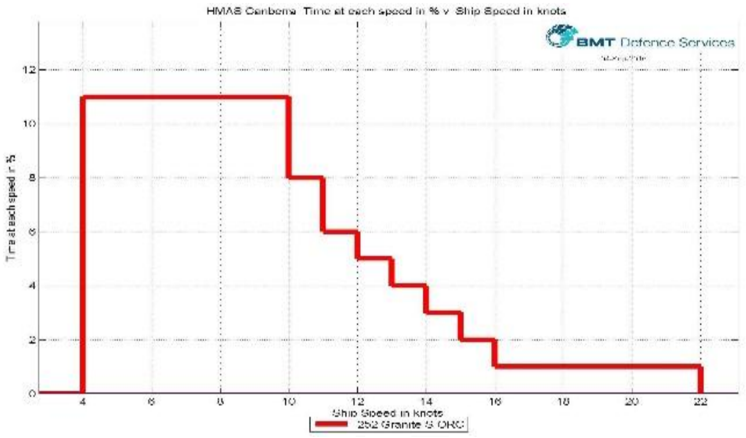

Figure 4. HMAS Canberra assumed operating profile

Figure 4 shows how the ship is assumed to spend much of its time at low speeds with little time spent at 17 knots and above when the GT genset would be in operation.

Figure 5 shows the estimated engine loads across the whole speed range. The ship can run on two diesel engines up to 16 knots after which the GT genset is run with one diesel genset set assuming single generator operation is not permitted. At 21 knots all three main gensets are operating at 75.2%. In harbour one diesel genset supplied the harbour load at 20 % load.

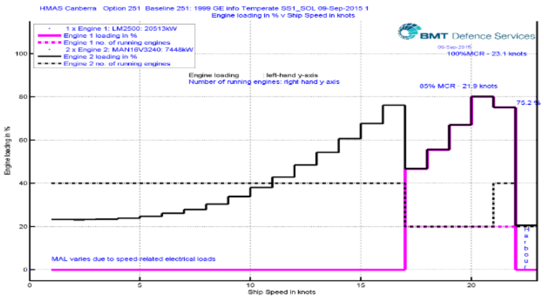

Figure 5. HMAS Canberra estimated engine load for the whole speed range

Figure 6 shows the total fuel consumption rate (kg/h) versus ship speed (knots)

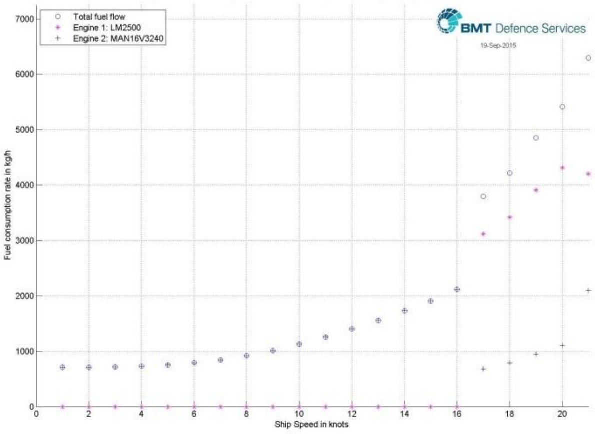

Figure 6. HMAS Canberra baseline total fuel consumption rate versus ship speed

Figure 6 shows how the use of the GT genset leads to a significant increase in fuel consumption due to its poorer specific fuel consumption (Sfc).

7. SHIP FIT

The body of plant comprises the fluid heater, the recuperator, the pump, condenser and turbine-generator.

The fluid heater would be located nearly in-line with the existing exhaust trucking, most likely in the uptake casing. The remaining equipment would be installed lower down to reduce the impact on ships stability, and ideally located on a common skid. However, the system equipment can be spread apart from each other to utilise available space in a retrofit installation, although the extra piping between the equipment will increase the total installed weight. As the fluid is non-flammable, it can be safely installed in a machinery space.

A longer post-WHR exhaust gas ducting with denser exhaust gas flows may lead to lower pressure drop and may mitigate the pressure drop losses over the WHR unit.

Table 4. Summary of DE Principal Equipment

Item	Size – HxWxD	Weight Tonnes
DE exhaust gas collector / fluid heater	2.6 X 2.2x 2.0	7.5
DE SORC Recuperator	1.7 x 1.6 x 1.7	4.5
DE SORC Condenser	1.5 x 0.8 x 2.1	1.8
DE ORC Expander / Turbogenerator	1.2 x 0.8 x 0.8	1.8
DE SORC wf motor-pump	1.4 x 0.35 x 0.35	1.5
Inverter & control cabinet	3.6 x 0.8 x 2.0	2.0
DE SORC SW motor-pump		
Other equipment		2.0

Each diesel SORC system is estimated to weigh 25 tonnes wet with the GT fit estimated to weigh 110 tonnes wet. This indicates the ship would have a total additional displacement of up to 160 tonnes. The additional displacement of 160 tonnes represents 0.6% of the total ships weight: this should be capable of accommodation through the ship's through-life growth margin.

8. INSTALLED SORC PERFORMANCE

The refrigerant R134a was used as the wf for both the GT and the DE SORC systems. The air temperature of 15°C allows the GT engine to operate with a performance at ISO conditions. The diesel engines also operate at their ISO rating (usually specified at 25°C).

8.1 GT SORC

When a SORC system was applied to the GT engine, the GT genset power rating is increased by 7,000 kWe to 28,725kWe. The GT genset and SORC package then provides an improved overall specific Sfc as shown in Figure 7.

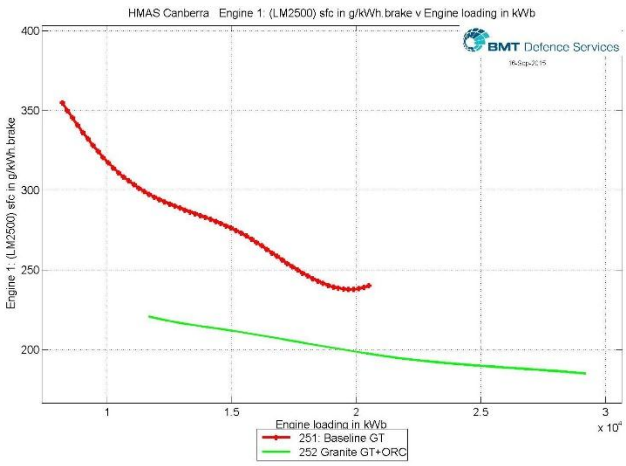

Figure 7. GT engine Sfc characteristic with and without the SORC system

Figure 7 shows how the addition of the SORC system rated at 7,000kWe to the GT genset greatly reduces the fuel required to generate each kW across the GT load range and also increases the total rated power.

8.2 DIESEL SORC

Figure 8 shows the Sfc characteristic of the MAN 16V32/40 genset with and without the addition of the SORC

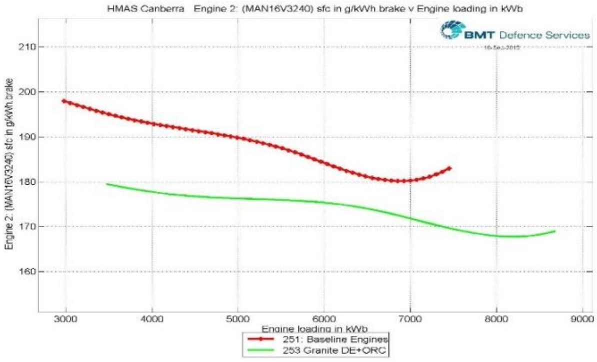

Figure 8. Diesel engine Sfc with and without the SORC system

Figure 8 shows how the MAN 16V32/40 Sfc characteristic is also modified by the 850KWe SORC system. The given efficiency of the SORC system is used to find the useful power output of the SORC set in kWe.

Figure 9 shows the total fuel consumption for all main engines across the ship's speed range for the baseline ship and the baseline ship with all main genset engines supplemented with an SORC system. When the ship's operating profile is taken into consideration Figure 10 shows the different fuel consumption pa at each ship speed.

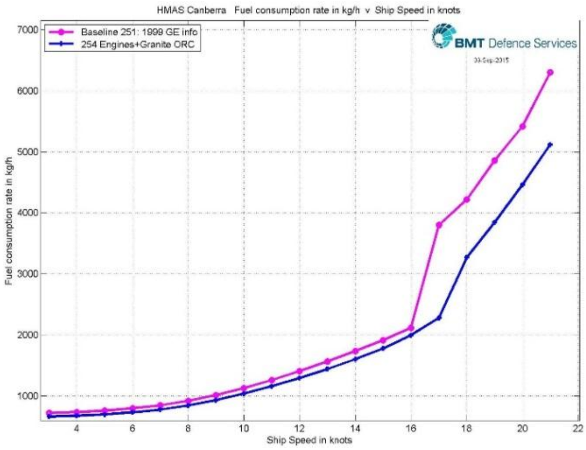

Figure 9. Comparative fuel consumption rates

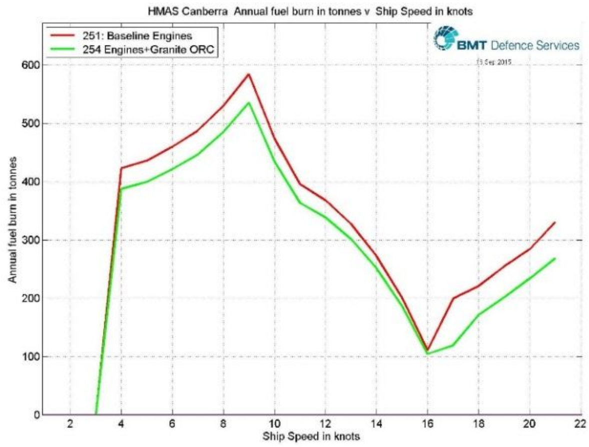

Figure 10. Relative fuel consumption at each speed

One of the benefits of larger rated diesel gensets is that they may allow the ship to operate at 1 knot faster before the GT genset needs to be started. At 21 knots only the GT plus one diesel genset need be run instead of all three main gensets. This also leads to a reduction in total main engine running hours and an estimated engine upkeep support cost saving of £150,000.

If only the main diesel gensets have the SORC system fitted the annual fuel saving is 8.0%. If the GT alone has an ORC applied then the annual fuel saving is 3.1%. This low figure is due to the fact that the GT genset is only run a few hundred hours a year. If all three main engines have the SORC fitted the annual fuel saving is 11.1%.

9. ENDURANCE

The ability of a warship to have a long reach for the amount of fuel embarked is a key feature which affects the fuel logistic supply chain. Figure 11 shows how the introduction of SORC affects the ships relative range performance due to the prescribed endurance requirements for 6,000 nm at 20 knots.

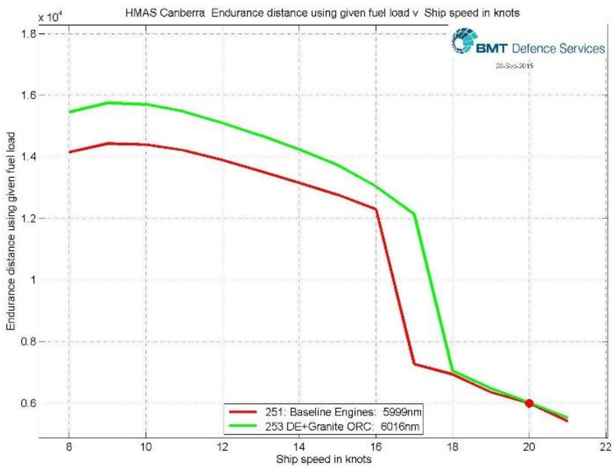

Figure 11. Relative endurance distance reference 20knot requirement

Figure 11 shows how the application of SORC to both DE and GT gensets leads to a reduction in bunker fuel consumption and storage requirement from 1625 tonnes to 1385 tonnes. The figure shows using the changes to engine cut-in points and how the relative endurance at other speeds can vary.

10. RELIABILITY & SAFETY

The equipment presented for the SORC systems applied to both gensets are both proven to be reliable through many hours operating experience. The SORC is likely to be more reliable than the diesel engine and for both engine types, the design allows for a by-pass to avoid the risk of over-heating and degrading the refrigerant and also to allow for engine operations with the SORC not in use.

11. COSTS

The acquisition cost for the 900kW SORC plant for each diesel engine is estimated to be £1.33m ($2m USD). Ship-board installation costs for both SORC are estimated to be £1.33m.

If the cost of fuel is £700/tonnes then the total saving per year due to reduced fuel consumption is £0.31m. With a total cost for onboard installation of £3.99m, this leads to a payable period of 13 years. With the use of the SORC when alongside this payback falls to 10.3 years in-service. In this period the increasing cost of fuel will bring this forward to below ten years.

12. CONCLUSIONS

The super-critical ORC technology offers useful and achievable fuel economy savings of 8% on average when used on the diesel engines of HMAS Canberra. The technology does not require fine matching with the engine and can be retrofitted to ships providing there is sufficient space in the casing.

The technology allows a better machinery operating regime to be achieved and the ship operates at a higher speed with just two main gensets. The SORC technology benefits from the cooler sea water temperatures to be found in Northern European waters as this allows a greater temperature range and a higher Carnot cycle efficiency. The SORC system comprises individual units which can be located flexibly around the machinery rooms to accommodate the total volume of the system.

This study has concentrated on the application of a SORC system to the HMAS Canberra and shows that with an SORC fit to each of the main diesel engines, a useful cost saving and range extension is achieved together with a payback of ~10 years.

The super-critical ORC system presented here has been developed and is proven on land. It is ready for its full potential fuel efficiency to be realised. Although it has been developed in land-based conditions such as geothermal applications, a ship-based solution should require further little design and development to allow it to be qualified by a marine classification society.

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