Journal of ELECTRONIC MATERIALS, Vol. 39, No. 9, 2010
DOI: 10.1007/s11664-010-1189-1

Potential for Usage of Thermoelectric Generators on Ships

N.R. KRISTIANSEN[1,2,3,4] and H.K. NIELSEN[2]

1.—Technical Department, TeamTec AS, 4902 Tvedestrand, Norway. 2.—Faculty of Engineering and Science, University of Agder, 4898 Grimstad, Norway. 3.—Department of Energy Technology, Aalborg University, 9100 Aalborg, Denmark. 4.—e-mail: nrk@teamtec.no

The useful waste heat potential for a bulk carrier has been evaluated as a preliminary step towards developing a thermoelectric generator (TEG) waste heat recovery system for ships. A medium-sized bulk carrier produces 6.2 MW of waste heat, and the most promising usable sources for the TEG are shown herein to be the exhausts from the main engine and the sludge oil incinerator.

Key words: Ship, waste heat recovery, thermoelectric generator (TEG)

INTRODUCTION

Ships are still the most efficient mode of transport when all environmental aspects are taken into account.[1] More than 80% of all goods shipped in the world are transported on ships.[2] Ship transport generates a large amount of waste heat, which is today to some extent utilized as thermal and rarely as electrical energy. Ships normally have waste heat of a quantity and quality to cover all demands for thermal energy onboard. This makes electrical power generation from waste heat interesting. Turbine-based systems exist, but these need large engines to be attractive. However for smaller engines and other waste heat sources, thermoelectric generators (TEGs) represent a promising solution. Clearly important factors for success in applying TEGs are commercialization of results from materials research and reduced price/Watt power output of the TEGs.[3]

OVERALL POTENTIAL FOR TEG APPLICATION

Waste heat sources on ships, ranked in decreasing magnitude, are: engine exhaust, scavenge air cooling,* engine cooling jacket, lubricating oil cooling, and incinerators. In addition, cargo cooling could make a substantial contribution for some types of ships such as reefer and container ships. The usability of the different waste heat sources is dependent on the fluid medium, the temperature level, the available power, and the power concentration.

ENGINE: WASTE HEAT TYPES AND CHARACTERISTICS

The main heat source onboard is the main engine. The Sankey diagram in Fig. 1 shows the different fractions of waste heat for a main engine installation both with and without electric power generation. The latter is more common. The example in Fig. 1 is a very efficient engine, yet still there is potential for alternative technologies such as TEG to recover more of the waste heat. Traditionally, waste heat is used for heating of heavy fuel oil, accommodation areas, and for freshwater generation. This decreases the available temperature levels.

INCINERATORS

In general, shipboard incinerators are designed to destroy waste material in an efficient manner such that the onboard crew prefer to incinerate their waste rather than polluting the ocean by throwing the waste overboard. The design criteria call for long operation time, compact installation, and easy operation. Incinerators have not been very attractive as a heat source for ships, mainly because of the limited running time and insufficient need for additional heat sources. In addition, introducing a

(Received July 8, 2009; accepted March 8, 2010; published online April 2, 2010)

*Scavenge air is the air fed to the engine for combustion and flushing of exhaust from the cylinders.

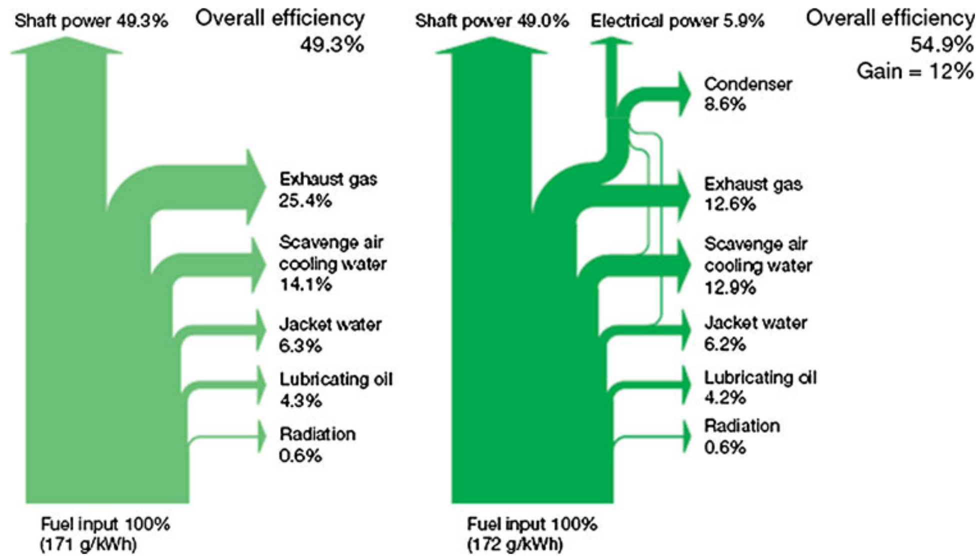

Fig. 1. Heat balance Sankey diagram of Wärtsilä-Sulzer RTA-96C.[4] The diagram on the right shows a waste heat recovery system based on a steam and an exhaust turbine.

Fig. 2. TeamTec OG 200C incinerator, representing a waste heat source with high temperature. *Source*: TeamTec.

boiler calls for additional safety measures and extra installation. However, an incinerator might be a good candidate for the introduction of TEGs. The incinerators have a high available temperature difference, and the general characteristics of the TEG comply with the design criteria given above for the incinerator. The capacity of an incinerator is normally matched with the bunker oil consumption of the main engine. Approximately 2% of the bunker oil is separated off as sludge. Of the sludge, 50% is drained off as free water, leaving a sludge containing about 25% water. The capacity of an incinerator should be 1.5% of the bunker oil consumption with an operating time of 50% (operation time could be up to 100% on ships with large engines without solid waste combustion). Assuming 50% main engine efficiency, the incinerator capacity in kW should be 3% of the main engine power in kW,[5] i.e., the 465 kW incinerator in Fig. 2 suits engine sizes up to 15 MW.

CARGO COOLING

All ships have some cooling systems installed, whether only for food storage, cooling, and air conditioning, or larger systems for cargo cooling. These systems normally consist of a compressor-based heat pump system and represent waste heat sources. However, the cooling of the condensation stage is designed for ambient sea temperature levels and it would normally not make sense to utilize this heat. Instead it would be better to optimize the design to reduce the power consumption of the cooling systems.

CASE STUDY

Typical ship sizes for the three largest classes of ships (bulk ships, container ships, and tankers) are given in Table I. A detailed study of the waste heat availabilities and usabilities was done on a ship close to the median size of bulk carriers.

The M/V Rosita, a typical bulk carrier of 52,000 deadweight tonnage (DWT) (Fig. 2), has been studied for a more detailed analysis of waste heat potential. The M/V Rosita has a main engine of 7.8 MW installed shaft power as the prime mover and three sets of 480-kW auxiliary engines for electricity production. However, the normal running condition is 85% load on the main engine, called the continuous service output (CSO). The Rosita accommodates a crew of 23 persons (Fig. 3).

Table I. Most common types of ships in Clarksons[6]

Type of Ship	Number	Median DWT (Mg)	Median Installed Power (MW)
Bulk carrier	8500	55,100	8.5
Tankers (oil and chemical carriers)	6800	31,540	7.1
Container ships	5900	30,740	15.3

Fig. 3. M/V Rosita managed by Ugland Marine Services AS is a typical bulk carrier. The engine of 7.8 MW represents a large source of waste heat. *Source*: Ugland.

ESTIMATION OF TEG POWER

The TEG power is estimated using the calculated efficiency of the TEG times the available thermal heat. The available thermal heat is estimated from the test reports, except for the flue gases. The usable thermal heat in the flue gases is calculated by the temperature difference between the actual flue gas temperature and a lower temperature limit of 160°C, chosen to avoid corrosion. The hot-side T_h of the TEG is taken to be either the average of the actual temperature and the lower temperature limit of the flue gas, or the actual temperatures of the heat exchangers. The cold-side temperature T_c is limited by the ambient seawater temperature, and for the worst-case scenario, tropical conditions are used and T_c is set to 29°C. The efficiency of a TEG is dependent on the temperature difference between T_h and T_c and on the figure of merit Z. For our purposes it is reasonable to assume a constant $Z = 0.002$, and employ the formula given below for efficiency η at maximum power output[7]:

$$\eta = \frac{T_h - T_c}{\frac{3T_h}{2} + \frac{T_c}{2} + \frac{4}{Z}}.$$

The main engine is the major source of useful waste heat. Based on Table II, the gases are the most interesting waste heat sources on board, as TEGs normally have higher efficiency at high temperatures. On the other hand, gases have much lower heat transfer coefficients compared with liquids. Only 20% of the available waste heat is in liquid form and the rest is represented by gaseous flows (Fig. 1). Scavenge air and the exhaust have the largest usable potential of those provided by the main engine. Scavenge air has a larger TEG power potential than the exhaust because of the different outlet temperatures: 43°C and 160°C, respectively. According to the manufacturer,[9] the total dissipated heat from the scavenge air is 3340 kW.

Besides the power levels, the running time is important when evaluating the total energy outputs. According to the machinery reports, the running hours on M/V Rosita were 4762 h/year

Table II. Waste heat sources on the M/V Rosita

Heat Source	Medium	Temp. (°C)	Quantity	Estimated TEG Power (kW)
Electrical generating unit	Flue gas	340	0.69 Nm^3/s[a]	10.0
Incinerator	Flue gas	340	0.68 Nm^3/s	9.7
Main engine exhaust after boiler	Flue gas	210	14.18 Nm^3/s	42.4
Main engine scavenge air cooling	Air	162	13.92 Nm^3/s	46.4
Excess steam from boiler	Sat. steam	159	0.087 kg/s[a]	5.9
Main engine cooling water	Fresh water	83	18 kg/s	11.8
FW generator unit, boiling water	Fresh water	61	8.3 kg/s[a]	4.3
Lubrication oil cooler	Lubrication oil	49	46 kg/s	2.1
FW generator unit, condenser	Salt water	37	25 kg/s[a]	0.4

Values were collected from the test records of the official sea trial at CSO,[8] main engine room data by MAN,[9] and machinery reports. Incinerator values are not for the installed incinerator but for a similar TeamTec OG 200C incinerator. [a]Values are calculated. *FW* fresh water.

averaged over the last 4 years. Besides the main engine, one of the three installed electrical generating units is normally running constantly. This only runs at approximately half load to supply the demanded electrical power consumption, which averages 271 kW_e.

The incinerator runs considerably less than the main engine, as it is normally running only in the daytime during the voyage. In the combustion chamber the available temperature is 1150°C prior to dilution with ambient air, which decreases the flue gas temperature to 340°C, as listed in Table II. The high temperature in the combustion chamber can be utilized, but would require a redesign of the incinerator. This has not been accounted for in Table II. Exhaust from the main engine is utilized for steam production. The steam heats the bunker oil and the accommodation areas. The surplus steam is condensed using seawater. The amount of excess steam varies considerably with the ambient conditions. In this paper an excess of 25% steam is assumed for the M/V Rosita.

DISCUSSION AND CONCLUSIONS

Although the main engine produces the vast majority of waste heat onboard ships, the quality of the heat is low, as some of the heat has already been utilized. In order to take advantage of the main benefits of TEG such as modularity and flexible design, it is reasonable to focus on smaller heat streams with higher temperatures that have not been utilized already. The flue gas from the auxiliary engines is also interesting, but normally only one out of three is running during sea voyages and all generator sets have separate flue gas stacks. A TEG installation in the waste oil incinerator has potential to utilize the high temperature in the combustion chamber and seems to be the best candidate for further study.

FUTURE WORK

Incinerators have been selected as the most promising application of TEGs by the company TeamTec, essentially because the incinerators have interesting temperature levels and the company has extensive experience with sludge oil incinerators.

In order to compare TEG module performance objectively,[10] a test station has been developed. The goal for the test station is to be able to test modules at high temperature and to incorporate a control system that allows dynamic testing. Another feature of the test rig is the possibility to vary the temperature gradient over the surface of the TEG module. This feature enables us to verify three-dimensional (3D) modeling of the TEG module behavior with a greater level of accuracy than with a uniform temperature in the heating element.

REFERENCES

1. World Shipping Council. http://www.worldshipping.org/benefits-of-liner-shipping, 25 January 2010.
2. United Nations, *Review of Maritime Transport 2008, United Nations Conference on Trade and Development* (2008). ISBN 978-92-1-112758-4.
3. J. Yang and F.R. Stabler, *J. Electron. Mater.* 38, 1344 (2009).
4. Wärtsila. Waste heat recovery, *Leaflet* (2007), 6 p.
5. O.J. Thorsen, personal message, TeamTec AS, (2009).
6. http://www.clarksons.net/ts/chart.asp#, 2 March 2009.
7. D.M. Rowe, *Thermoelectrics Handbook Macro to Nano* (Boca Raton, FL: CRC/Taylor & Francis, 2006), pp. 1–4.
8. Tsuneishi Corporation Tsuneishi Heavy Industries (CEBU) Inc.: *Rosita VI Test Record of Official Sea Trial, Machinery Part*, Internal Report (2004), 17 p.
9. MAN Diesel SE, *Main Engine Room Data* (2009). http://www.manbw.dk/seas/erd.
10. L.E. Bell, *J. Electron. Mater.* 38, 1245 (2009).