Waste Heat Recovery from a Marine Waste Incinerator Using a Thermoelectric Generator

N.R. KRISTIANSEN,[1,3,4,5,6] G.J. SNYDER,[2] H.K. NIELSEN,[3] and L. ROSENDAHL[4]

1.—Technical Department, TeamTec AS, 4902 Tvedestrand, Norway. 2.—Materials Science, California Institute of Technology, Pasadena, CA 91125, USA. 3.—Faculty of Engineering and Science, University of Agder, 4898 Grimstad, Norway. 4.—Department of Energy Technology, Aalborg University, 9220 Aalborg, Denmark. 5.—e-mail: nils.r.kristiansen@teamtec.no. 6.—e-mail: nrk@teamtec.no

A marine waste incinerator has been evaluated for waste heat harvesting using thermoelectric generators (TEG). The application has been evaluated using mathematical modeling to optimize the heat exchanger and some vital design parameters of the TEG. The calculation shows that it is possible to extract 58 kW_{el} at a price of 6.6 US\$/W from an 850-kW_{th} incinerator when optimizing for maximum power. However, minimizing the cost, it is possible to get 25 kW_{el} at a price of 2.5 US\$/W. A trade-off between the two targets leads to a combination that gives 38 kW_{el} at a price of 2.7 US\$/W.

Key words: Marine incinerator, thermoelectric, TEG, mathematical model, waste heat, waste heat recovery

INTRODUCTION

Waste heat harvesting by thermoelectric generators (TEG) is not common practice. The main reason for this is lack of commercially available high-temperature thermoelectric (TE) modules, and the relatively high expense of such a system on a US\$/W basis. This study analyzes one particular application, namely harvesting waste heat from a waste incinerator for marine use. The potential for utilizing waste heat from ships is generally promising, especially from incinerators,[1] because none of the energy released during combustion is normally utilized.

A marine incinerator is primarily used to burn sludge. Sludge is a waste oil/water fraction from preparing heavy fuel oil before it is used in diesel engines on board ships. The incinerator is also used to destroy any solid waste generated on board, typically from packaging and normal household waste. The heat from combustion is not used for electricity generation because of an intermittent running pattern and relatively small energy quantities. It is not used for heat because the heat demand on board is well covered by an exhaust boiler on the main engine. Incinerators range in size from 2 m^3 to 16 m^3 and 210 kW_{th} to 1500 kW_{th}. Approximately 2000 ships are built every year with incinerators. In total, 42,000 commercial ships larger than 300 dead weight tonnes and with propulsion power larger than 1 MW, not counting passenger and special operation ships, were in service in 2011 according to the Comprehensive Ships, Companies & Ship Builders Database from IHS Fairplay (www.sea-web.com). It can be estimated, based on the total consumption of bunker fuel,[2] that 4.5×10^7 GJ of energy from sludge oil is incinerated every year on ships.

Typical operation costs of an incinerator amount to man-hours and electricity consumption, which is mainly due to the flue gas fan and varies with the size of incinerator. The smallest ones use less than 8 kW and the largest ones up to 40 kW. In addition there is some diesel consumption during the start-up phase of the incinerator. Typical operation is to run 8 h to 12 h a day with daily start-up and shut down in order to clean out ash from solid waste combustion. On some larger installations, more continuous operation is common. Normally, the incinerators are dimensioned with excess capacity to allow sludge produced in waters or

Fig. 1. Diagram of a typical shipboard incinerator (TeamTec OG200C).

Fig. 2. Design of TEG heat exchanger with modular cross-section for installation in the flue from a waste incinerator.

ports where incineration is prohibited to be incinerated later.

Ships have a seawater heat sink with average temperature of 5°C to 30°C, depending on where they sail, readily available. The high combustion temperatures and efficient heat sink make incinerators ideal for TE-based waste heat recovery.

An efficient steam turbine design would have a higher efficiency, but add significant man-hours to the ship because of daily start-up and shut down of incinerator and hence the steam system. As the cost of additional personnel is prohibitive on board a ship, the low-maintenance aspect of TE makes TEG attractive.

TE incinerator design may be used for other incinerator applications such as land-based garbage incineration or other high-temperature waste heat sources. However, if the hot gas is cleaner than the flue from marine incinerators, the heat exchanger can be made more efficient and cost and weight can be reduced (Fig. 1).

DESIGN

A number of locations for a TEG were initially considered. For maximum electrical power conversion, both heat flow and temperature difference must be considered. There are principally two places on an incinerator to implement TEG for waste heat harvesting: in the combustion chamber or in the flue after the incinerator. This study concentrates on the flue gas in order to avoid affecting the combustion process. The design shown in Fig. 2 is chosen based on a few assumptions and reasons. The inside of the flue gas channels need to be fin-free in order to avoid build-up of particles and to ease removing of particles that do build up.
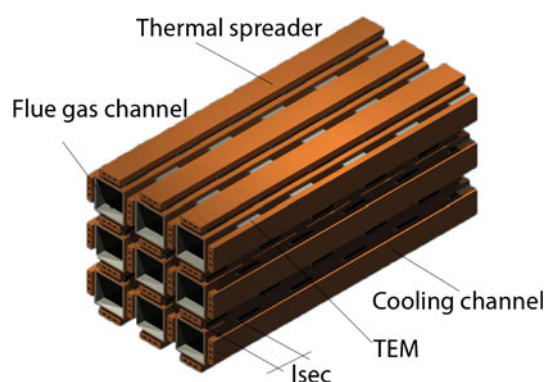
The cross-section needs to be modular so that the design can work for different design flows due to the large variation of incinerator sizes. The design is built up of sections in the length direction, with a variable length. This still leaves many design parameters to optimize in the following mathematical modeling. The main parameters of interest are related to adjusting the thermal conductance of the TEG and heat exchangers to maximize power output. In general, the thermal conductance of the TEG should be matched to the thermal conductance of the heat exchangers for maximum power,[3] and the thermal conductance of the heat exchanger should be as high as possible to maximize power density, which reduces weight and therefore cost. This generally leads to half the available ΔT being across the TEG.[3]

For ease of mass production, it is further assumed the TE modules will be identical (or of a very limited number of types), thus the area of each module is fixed and the relationship between module area and flue gas surface area is taken care of by enabling the section length, l_{sec} (Fig. 2), to be changed. The number of sections is fixed, but could have been an optimizing factor as well.

The growth factor f_{ls} is a fraction that describes how much longer the next section is compared with the previous, as described in (1). This results in a heat exchanger consisting of sections in the length direction that increase in length. Applying this growth factor enables the design to keep the temperature difference across the TEM high for a larger portion of the heat exchanger. A relatively larger area means a relative higher heat flux and hence relatively larger temperature difference across the module.

$$l_{sec_{i+1}} = f_{ls} \cdot \frac{l_{sec_i}}{1000}. \tag{1}$$

The TEG thermal conductance/area is determined primarily by the filling factor of the thermoelectric modules (TEM), that is, the area of TE material/area of TE module, the thickness of the TE module, the length of each section, and the growth of section length.

CHOICE OF MATERIAL

The flue gasses from a waste incinerator are generally somewhat corrosive, depending on the waste being burned. In addition to general requirements such as good thermal conductivity, mechanical strength at elevated temperatures, and low cost, the material for the heat exchanger should have good corrosion resistance. For this analysis, stainless steel grade 316 has been chosen for contact with the flue gas, and a layer of copper is applied as a thermal spreader after that. On the cold side of the TEG, a copper channel is chosen as the material for the water-cooled cold side. On each side of the TE module, there is a ceramic wafer for electrical insulation between the TE pairs.

CALCULATIONS

The calculations are based on a thermal circuit as shown in Fig. 3 of heat transfer from the flue gas to the heat exchanger and through the heat exchanger materials including TEGs and into the cooling fluid. The heat passing through the system can be modeled using a thermal circuit where the temperature difference ΔT is proportional to the rate of heat flow Q given by (2)

$$\Delta T = Q \cdot R_{\text{tot}}; \tag{2}$$

for example R_{tot} is the thermal resistance between the flue gas and the cooling water calculated based on Fig. 3, and the individual resistances are mainly based on engineering formulas from Gieck,[4] apart from the Nusselt number, which is found from the Gnielinski correlation. The analogy in formula (2) to an electric circuit is a one-dimensional model which has some limitations in accuracy; For example, the 1-D circuit does not explicitly account for thermal resistance within the components. To correct for this, spreading resistance is added from Ref. 5 using their online calculator to create a table for different thicknesses and different section lengths.

Temperatures are calculated based on the same framework and give the temperature difference across the TE module, T_{h} and T_{c}. The power from the TE module is calculated from the efficiency of the TE module and the portion of heat flowing into the modules' hot side, accounting for parasitic losses. For efficiency, Eq. 3 is used.

$$\eta = \frac{T_{\text{h}} - T_{\text{c}}}{T_{\text{h}}} \cdot \frac{\sqrt{1 + ZT} - 1}{\sqrt{1 + ZT} + \frac{T_{\text{c}}}{T_{\text{h}}}}. \tag{3}$$
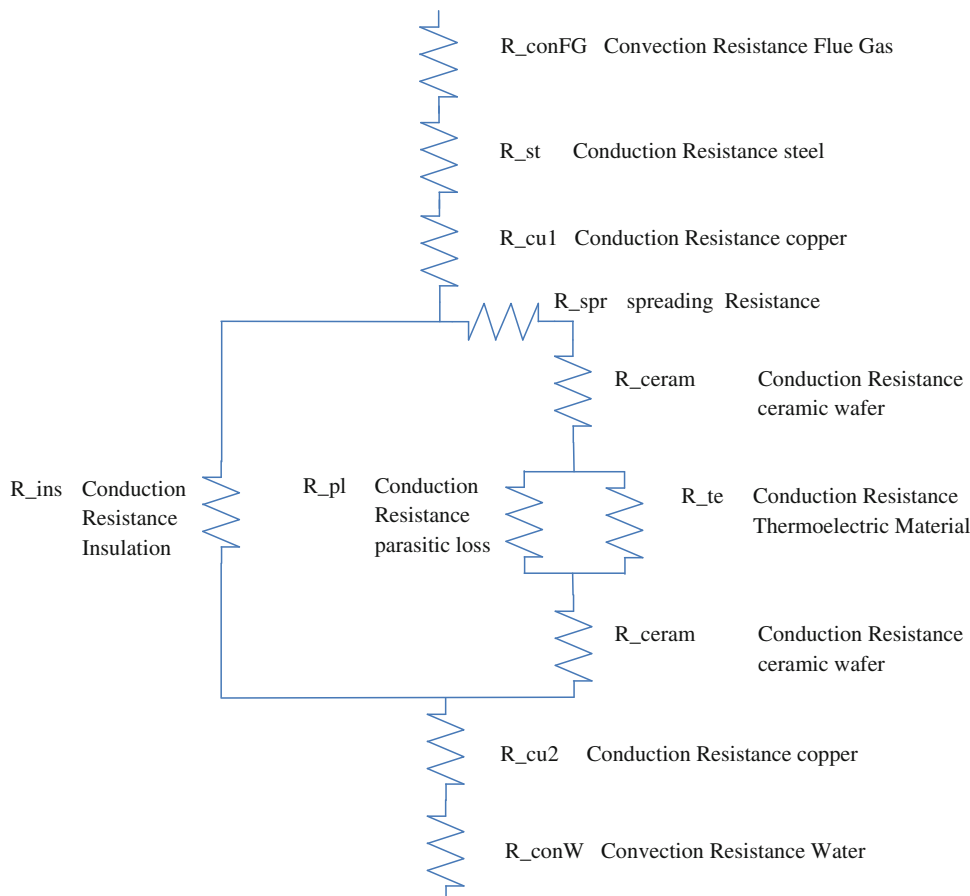

Fig. 3. Thermal circuit of one section of the thermoelectric generator.

For optimization purposes $ZT = 1$ is used, where ZT is the overall device figure of merit for a TEG. The net power gain in the calculation is the sum of the power produced by the TE minus the power for running an extra cooling-water pump plus the gain of reduced power consumption by the flue gas fan due to the reduced amount of cooling air.

All the formulas were incorporated in a Microsoft Excel spreadsheet. The design parameters given in Table I were optimized using a nonlinear generalized reduced gradient solver. The analysis allows for optimizing net power gain, optimizing system efficiency, and minimizing cost per watt of net power gain due to TE installation. The parameters that can be optimized for the TE module are the thickness of the module and the filling factor. For the geometry of the heat exchanger, the length of the first section is an adjustable parameter and the growth rate of the section lengths is a parameter. All adjustable parameters in the model are presented in Table I.

Limitations to all parameters were applied. Some are physical limits for engineering purposes, and some are set to limit the solver population range. There are minimum and maximum section lengths, where the minimum is slightly larger than the length of one module and the maximum is set to 0.4 m. The TEM has to be between 1 mm and 100 mm thick, and its filling factor has to be between 10% and 90%.

COST ANALYSIS

The cost analysis is based on a cost per kilogram plus a fixed cost. Prices are obtained from Norwegian suppliers of steel and metals, and the machining cost is a "rule of thumb" cost from a fabrication workshop. The prices used in the calculation are given in Table II.

RESULTS

Optimizing for maximum power and minimum cost per watt gives very different optimum points. The maximum power tends to find its optimum at the edge of some of the valid parameter ranges, and minimum cost per watt at the edge of other valid parameter ranges. The two different optimum points are described in Table III.

By optimizing for maximum power but limiting the cost per watt, it is possible to obtain a curve for maximum power at different costs (Fig. 4). At the lower cost end of the graph, a small change in allowed cost gives a large change in produced power. At the high cost end of the graph, a large increase of cost contributes only marginally to the net power.

The temperatures along the counterflow heat exchanger are displayed in Fig. 5. The profile of the flue gas temperature is characteristic for a heat exchanger, but the TEM hot-side temperature is more linear.

Another interesting analysis is to do the same optimisations for different ZT values. The graph in Fig. 4 shows the results for $ZT = 1$. In Fig. 6, similar graphs with different ZT values have been combined to form a three-dimensional (3D) surface. The flat area to the left in the figure is outside the valid range and can be considered as the minimum price per watt limit.

DISCUSSION

The maximum power and the minimum cost per watt do not appear for the same set of parameters. The curve in Fig. 4 is very steep close to the minimum cost point and flat near the maximum power. This means that it is beneficial to move towards higher cost per watt compared with the minimum cost. It also means that moving past 4.5 US$/W gives nearly no increase in power. Increasing the cost by 0.2 US$/W from the minimum point to 2.7 US$/W gives a power of 37.6 kW. The cost of TE material accounts for 24% of the total cost.

Table II. Material costs used in the cost analysis

Cost Item	Price	Unit
Stainless steel 316	10	US$/kg
Copper	12	US$/kg
TE material	250	US$/kg
Insulation	10	US$/kg
Building	8	US$/kg
Fixed cost	20,000	US$

Table I. Optimizable parameters in TE heat exchanger design

Parameter	Abbreviation	Unit	Min. Limit	Max. Limit
Section length, first section	L_{sec}	m	0.08	0.4
Growth factor section length	F_{ls}	‰	0	33
Thickness of stainless-steel wall	l_{wall}	m	0.003	0.01
Thickness of copper thermal spreader	l_{cu}	m	0.001	0.015
Thickness of thermoelectric module	l_{tem}	m	0.001	0.1
Filling factor of thermoelectric module	f_{tem}	−	0.1	0.9
Diameter of cooling-water channels	d_{cool}	m	0.01	0.02
Flow of cooling water	AQ_w	m³/h	5	20

Table III. Optimal solutions with regards to power and cost

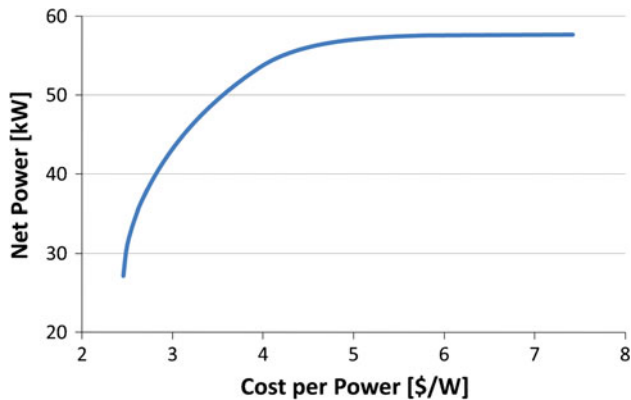| Parameter/Indicator	Value for Max. Power	Value for Min. US$/W	Unit
Power gain	57.7	27.4	W
Price per Watt	7.42	2.46	US$/W
Weight of heat exchanger	16,300	2,140	kg
Length of heat exchanger	17.1	4.0	m
First section length	180	80	mm
Growth factor section length	21.2	0	‰
Thickness of copper thermal spreader	15.4	1.99	mm
Thickness of thermoelectric module	12.1	4.7	mm
Filling factor of thermoelectric module	0.900	0.266	–
Diameter of cooling-water channels	0.01	0.01	m
Flow of cooling water	19.7	14.8	m^3/h

Fig. 4. Maximum power as a function of cost per watt.

Fig. 6. Net power gain from TEG at varying *ZT* and allowed price per watt of installation cost.
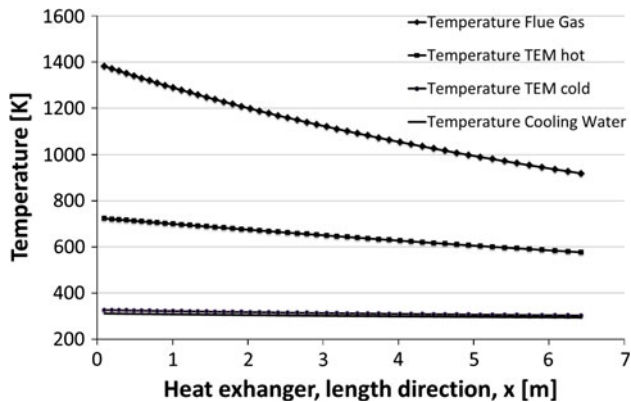

Fig. 5. Temperature distribution along the counterflow heat exchanger.

The system efficiency is normally considered to be the electric output divided by the latent energy of the fuel input. In this application, this is less relevant because it would reward less fuel input, whereas in this application the fuel input is waste to be destroyed and higher fuel input is desirable. On the other hand the amount of waste is a fixed quantity, so when an investment is made to produce electricity from the wa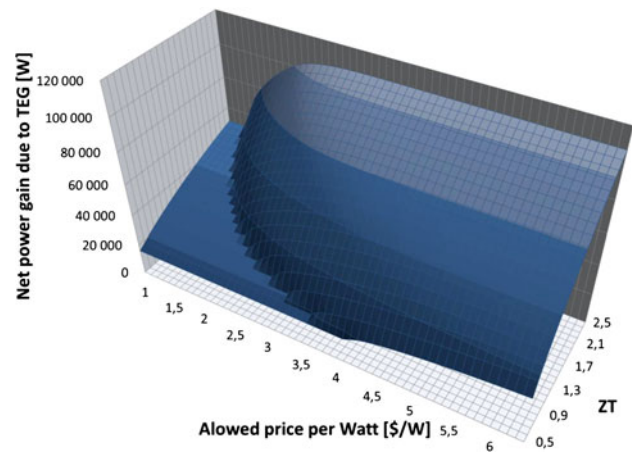ste, there is an incentive to produce as much electricity as possible from the amount of waste that is produced. In this application the interesting point to address is the gain in net electrical difference when adding the TEG to the incinerator. If the electric power demand on board is considered a constant, the addition of electricity produced by the TEG will reduce the load on the diesel generators and result in less consumption of diesel fuel. This would be the financing source to justify the cost of adding the TE system to the incinerator.

Allowing the cost per power unit to increase a little enables the power to increase greatly, but so then will the total cost. This means that allowing a higher price per power unit has a very dramatic effect on the total cost of the heat exchanger. It is arguable whether the true optimum is at minimum cost per watt or if it is permissible to allow a higher specific price in order to produce more power.

On a ship installation, the competing power source is diesel generator sets. Unfortunately installation of a waste heat recovery system producing electricity cannot justify installation of less power from the generator sets. This is due to safety concerns and power availability during maneuvering in ports, where incineration is prohibited. This

means that the whole installation competes with the fuel cost of running the generators.

The plot in Fig. 6 shows the importance of high ZT when a TEG is implemented in the system, however in this analysis the price of TE material is kept constant and does not depend on ZT. The same applies to the thermal conductance of the TE material, which should be a function of ZT to make this plot more valid. Still, it captures the relation between the cost of the TEG and the rest of the system, which is why the price per watt increases rapidly when ZT is reduced.

REFERENCES

1. N.R. Kristiansen and H.K. Nielsen, *J. Electron. Mater.* 39, 9 (2010).
2. Anonymous, Consumption of Residual Fuel Oil for Bunkering. International Energy Statistics http://www.eia.gov/cfapps/ipdbproject/IEDIndex3.cfm?tid=5&pid=66&aid=13. Accessed 25 February 2011.
3. G.J. Snyder, *Energy Harvesting Technologies*, ed. S. Priya and D.J. Inman (Boston, MA, USA: Springer, 2009), pp. 325–336.
4. K. Gieck and R. Gieck, *Engineering Formulas* (New York: McGraw-Hill, 2006), 580 pp.
5. M.M. Yovanovich, Y.S. Muzychka, and J.R. Culham, *J. Thermophys. Heat Transf.* 13, 4 (1999).