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Experimental research of thermal electric power generation from ship incinerator exhaust heat

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Abstract. Massive energy consumption and carbon emission has become one of the problems that limit the sound development of shipping industry. Ships without exhaust heat recovery, have massive heat discharged directly and wasted. Thermoelectric power generation (TEG) is an effective and environment-friendly technology to recover ships' exhaust heat. Based on previous research, this study mainly focuses on the recovery of exhaust heat produced by the incinerator on board, which is less researched before. Firstly, the operating parameters of typical incinerators on board are obtained and the available exhaust heat is calculated. Secondly, based on TEG, a scheme is made for incinerators on board to recover exhaust heat, and related experimental device is also set up. The heat recovery performance of the device is studied in several typical operating conditions of the incinerator. When the exhaust temperature reaches 450°C and 520°C, the TEG can produce a power of 776W and 882W respectively. The thermal efficiencies also exceed 4%, with an efficiency of 4.2% and 4.36% respectively. Thirdly, based on the experimental data, a TEG prototype for the incinerator on the YuKun ship is designed and its performance is evaluated. According to the estimation based on the experimental data, the TEG prototype, which has a length of 1 meter and is proposed in this dissertation, can theoretically produce a power of 9.45 kW.

1. Introduction

The ship transportation industry plays a decisive role in the development and prosperity of the world economy. However, the huge energy consumption and carbon emissions increasingly hinder its healthy development. On the one hand, the cost of energy consumption steadily increases. The data shows that energy costs account for a large proportion of the total operating cost for a ship [1]. For example, small transport ships account for about 25%-30%, regular passenger and cargo ships account for about 35%, bulk carriers account for about 50%, and oil tankers account for about 60%. On the other hand, the exhaust heat of the exhaust is huge. From the energy consumption of three main ship types by CCS [2], it is known that the exhaust takes away 15.9% of the energy input of the main engine and 11.9% of the total input energy of the ship. It means a lot of exhaust heat is wasted.

As a green energy recovery technology, thermoelectric power generation (TEG) has the advantages of no rotating parts, easy maintenance and no noise etc. It has been widely concerned and applied in the field of exhaust heat recovery after the improvement of material performance. Loupis et al. [3] recover the exhaust heat from marine diesel engine by TEG with seawater circulation as cold source. When the output of the main engine is 1700 kW, the output of TEG reaches 20.3 kW, and the system efficiency reaches 1.2%. Based on TEG, Georgopoulou et al. [4] propose a method for recovering the



exhaust heat from the air cooler and the generator of a VLCC by TEG. The results show that the output of TEG from the air cooler is about 26 kW, which is about 0.2% of the main engine's power. And the output of TEG from the generator is about 1 kW.

Compared with the main engine, there is less research on exhaust heat recovery for the ship incinerator, which is a kind of the marine pollution prevention equipment. It is used for the burning of oily sludge, sewage sludge and combustible solid waste on ships. According to maritime regulations [5], the temperature in the incinerator should be maintained between 850 °C and 1200 °C, and the outlet exhaust temperature should be below 350 °C. The traditional way is to cool down the exhaust by fresh water on ship. Hence massive heat is wasted.

Based on previous research [6-9], the exhaust heat of ship incinerator is analyzed after operating parameters of several typical ship incinerators are collected. Based on the characteristics of ship incinerator exhaust heat, a prototype of thermoelectric power generation from incinerator exhaust is proposed. The feasibility is verified by experiments and the performance is evaluated through experimental data.

2. Analysis of exhaust heat and set up of the experimental device

2.1. Analysis of exhaust heat from the ship incinerator

Table 1 shows the operating parameters of four typical ship incinerators. Due to the complex composition of waste material in ship incinerators, the combustion heat value is uncertain. Table 2 shows the approximate calorific value of ship waste combustion. The heat balance of the incinerator is defined as the state where the added heat is equal to the heat rejected by waste material and auxiliary fuel. The released heat is the sum of exhaust heat and heat diffused to the environment. In order to establish a high temperature (usually between 850 °C and 1200 °C) in the furnace and maintain it, the added heat should be equal to the discharged heat.

Table 1. Operating parameters of several typical types of ship incinerators.

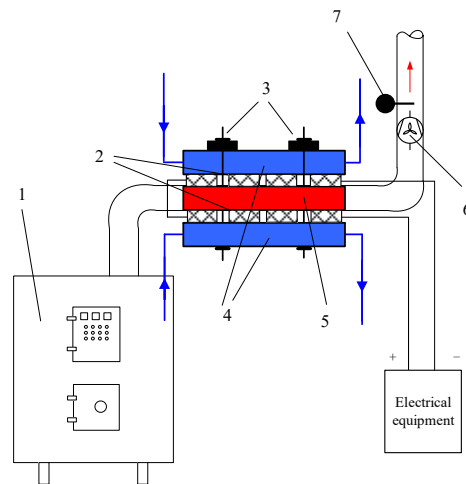
Model	Maximum Heat Capacity (kJ/h)	Waste Oil	Exhaust Temperature (°C)	Exhaust Volume
ATLAS 200	756000	24 L/h	250	6660 m ³ /h
HAMWORTHY	3150000	112 L/h	350	—
FD210C	752400	20 kg/h	280~350	—
OSV-600SAI	2160000	64 kg/h	350	13000

Table 2. Combustion heat of typical garbage on board.

Substance	Vegetables and Perishable Substances	Paper	Rag	Plastic	Waste Oil	Sludge
Heat Value (kJ/kg)	5700	14300	15500	36000	36000	3000

2.2. Exhaust heat utilization scheme

Based on the previous research and TEG theory, a scheme for the incinerator exhaust heat recovery based on TEG is designed, as shown in Figure 1. The solution can make the TEG unit fully contact with the exhaust pipe of the incinerator, which makes it easy to arrange and maintain the unit without damaging the internal structure of the pipeline. It also can ensure the maximum safety and reliability for the equipment. TE modules which can work under high temperature conditions are selected to improve the output. Due to the recovery of exhaust heat, the temperature of the exhaust reduces after passing through the TEG. Through Temperature control sensing device and variable-frequency fan, the temperature of the exhaust can be controlled below 350 °C. Not only can the exhaust heat be recovered, but also the cooling power for incinerator exhaust can be reduced.

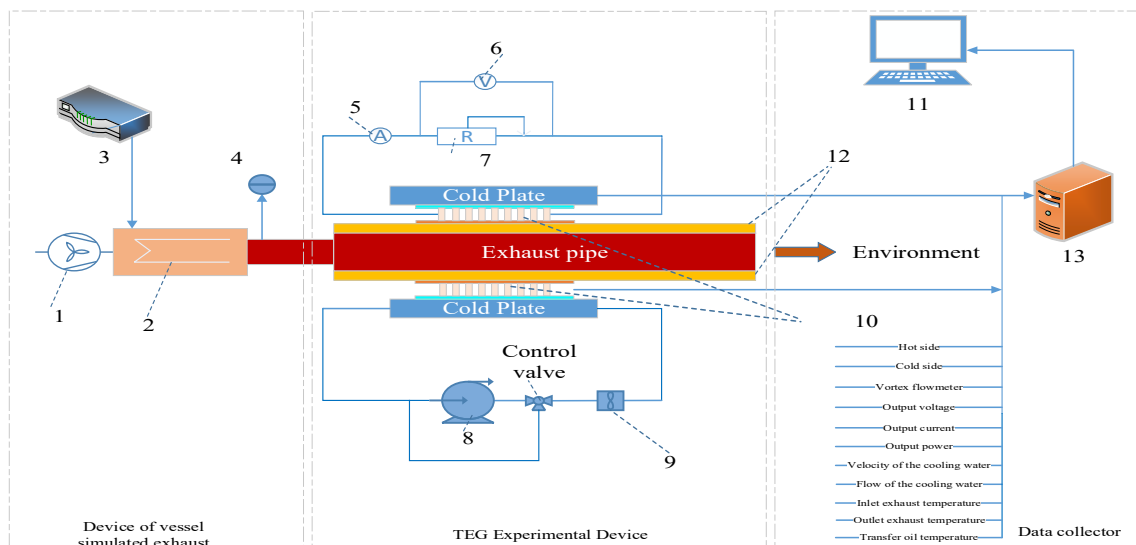


1) Incinerator 2) Thermoelectric module 3) Fastening bolt 4) Cold plate 5) Exhaust pipe 6) Fan 7) Thermocouple

Figure 1. TEG system for recovering the ship incinerator exhaust.

2.3. Design of the experimental device

The experimental device is shown in figure 2.



1) Fan 2) Heating device 3) Temperature control device 4) Vortex flowmeter 5) Ammeter 6) Voltmeter 7) Rheostat 8) Water pump 9) Water flowmeter 10) TE module 11) Monitoring unit 12) Heat transfer oil 13) Data collector

Figure 2. System diagram of the TEG experimental device.

The TEG is shown in figure 3. It's a structure with a shape of hexahedron outside and a shape of pipe inside. The diameter of the inner pipe is 100 mm, the thickness of the pipe is 6 mm, and the length of the pipe is 500 mm. The side length of the hexahedron is 75 mm, and there are 42 TE modules on the hexahedron. The 7 TE modules of each side are connected in series and the six sides are connected in parallel. The dimensions of the TE module used in the experiment is 56 mm × 56 mm × 4.5 mm. The maximum temperature of the hot side is 450 °C. When the hot side temperature is 300°C, the cold side temperature is 30 °C.

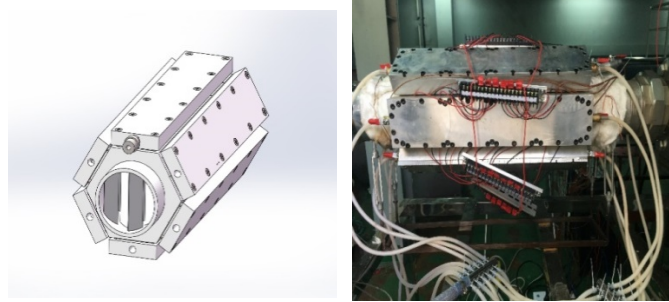


Figure 3. The TEG experimental device for recovering the ship incinerator exhaust.

3. Analysis of experimental data

Figure 4 shows the variations of temperature over time for each part of the experimental device in the working condition of optimal matching load and forced water-cooling. It can be seen from the figure that, with the temperature of the exhaust increasing, the temperature of the hot side, and the temperature difference between hot side and the cold side will increase, but the increment of the temperature difference between the hot side and the cold side, and the temperature difference between the exhaust and the hot side will decrease gradually. After the system is stable, there is still a temperature difference from 100 °C to 200 °C between the hot and cold side. It means that the thermal resistance between the exhaust and the hot side is large. The heat transfer should be optimized for further study.

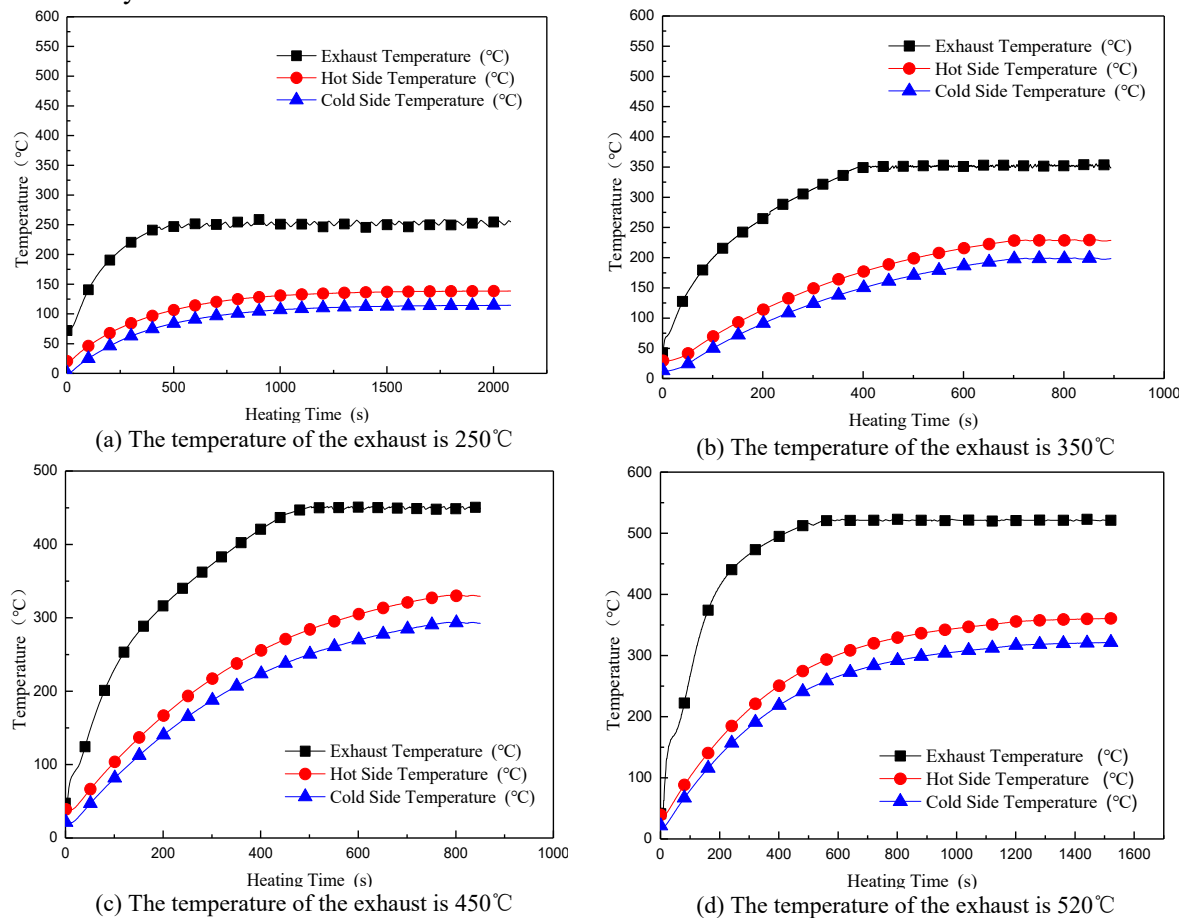


Figure 4. Variations of system temperature with different exhaust temperature.

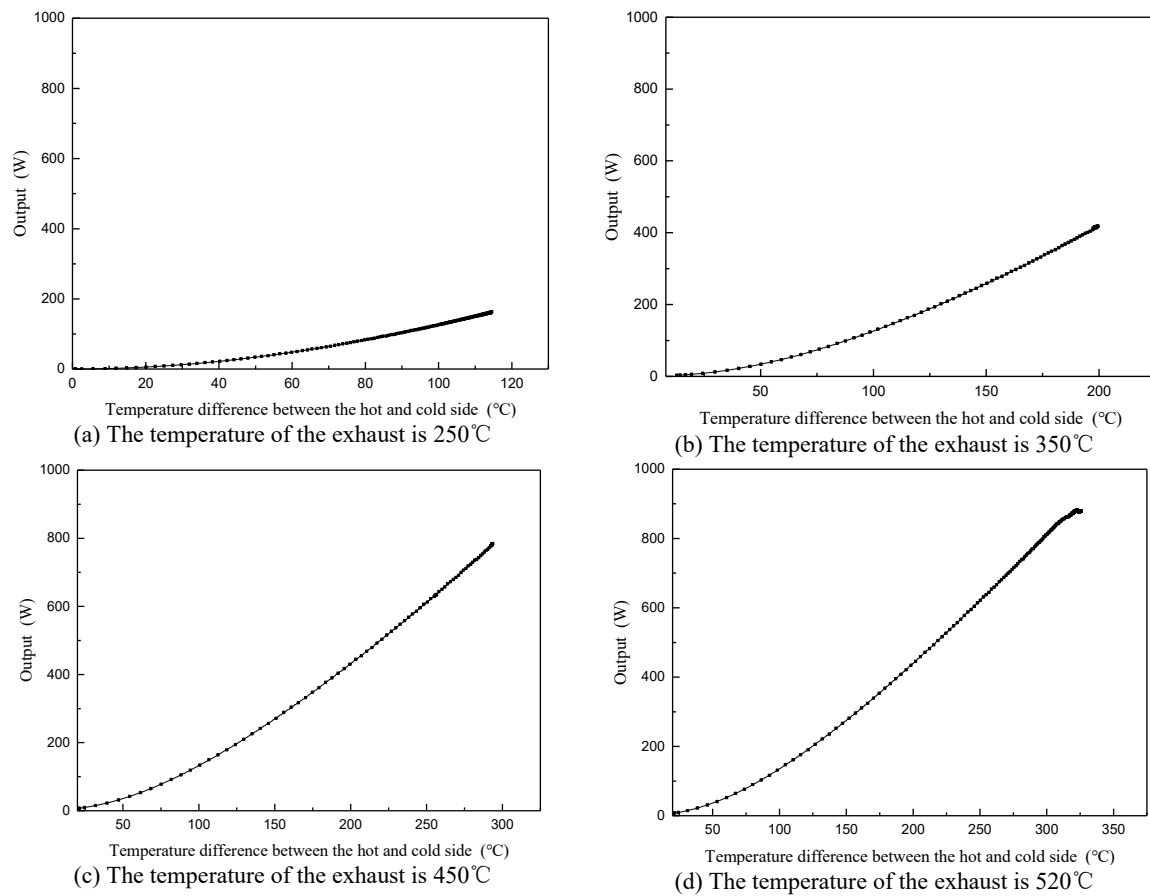


Figure 5. Variations of the power output with different temperature difference.

Table 3. Experimental data of the TEG device.

(i) Inlet Exhaust Temperature (°C)	(ii) 250	(iii) 350	(iv) 450	(v) 520
(vi) Outlet Exhaust Temperature (°C)	(vii) 228	(viii) 323	(ix) 416	(x) 485
(xi) Hot Side Temperature (°C)	(xii) 138.6	(xiii) 228.6	(xiv) 328.3	(xv) 365
(xvi) Cold Side Temperature (°C)	(xvii) 24.1	(xviii) 30.2	(xix) 36.9	(xx) 39.6
(xxi) Inlet Cooling Water Temperature (°C)	(xxii) 16	(xxiii) 16	(xxiv) 15.9	(xxv) 16
(xxvi) Outlet Cooling Water Temperature (°C)	(xxvii) 16.1	(xxviii) 16.1	(xxix) 16.4	(xxx) 16.5
(xxxi) Output Voltage (V)	(xxxii) 23.8	(xxxiii) 37.94	(xxxiv) 51.52	(xxxv) 54.67
(xxxvi) Output Current (A)	(xxxvii) 6.84	(xxxviii) 10.98	(xxxix) 15.06	(xl) 16.08
(xli) Output Power (W)	(xlii) 162.79	(xliii) 416.58	(xliv) 775.89	(xlv) 879.09
(xlvi) Thermal efficiency (%)	(xlvii) 1.94	(xlviii) 3.22	(xlix) 4.2	(l) 4.36

Figure 5 shows the variations of the output with different temperature difference between the hot and cold side. It can be seen from the figure that the output of the device increases as the temperature difference between the hot and cold side rises. And the changing trend is gradually rising. It can be known from figure 5 (d), when the temperature difference between the hot and cold side is greater than 100°C, the output increases by about 35 W per 10°C. And the figure shows that the output is very low when the temperature difference is under 120°C. When the temperature difference is 325°C, the output of the device reaches 879 W.

At four distinctive temperatures of incinerator's exhaust, the performance of the prototype is evaluated. The related data is shown in Table 3. It can be known from the table that the thermal efficiency increases as the exhaust temperature rises. When the exhaust temperature is 450°C and 520°C, the thermal efficiency of the device can reach 4.2% and 4.36%.

Referring to the experimental data, a TEG prototype for recovering exhaust heat from the incinerator on YuKun ship is designed. The diameter of the exhaust pipe is 530 mm, the thickness of the pipe is 5 mm, the side length of the hexahedron is 320 mm, and the size of the TE module is 60 mm × 60 mm. It can be known from the experiment data that, the average output of each TE module is about 20 W while the exhaust temperature is 520°C. The length of the prototype is 1 m. There are totally 450 TE modules employed in the TEG device, with 75 TE modules on each side. From the experimental data, it can be roughly estimated that when the exhaust temperature is 520°C, the maximum output of the prototype can reach about 9.45 kW theoretically.

4. Conclusions

Based on the research in the performance of the TEG in the typical working conditions of incinerators, a conclusion can be drawn that when the exhaust temperature reaches 450 °C and 520 °C, the TEG can produce a power of 776 W and 882 W, with an efficiency of 4.2% and 4.36% respectively, which verifies the feasibility of this conception. Based on the experimental data, a TEG prototype for the incinerator on Yu Kun ship is designed. This generator can produce a power of 9.45 kW theoretically.

Exhaust heat on board is massive, widespread and produced in multiple way. Nowadays, various recovery methods are needed for various exhaust heat on board, which costs more, makes it difficult to carry out maintenance and lower the utilization ratio of exhaust heat. The next step is mainly to research in the comprehensive utilization of ships' exhaust heat. With one or more types of combined cycles, it's hoped to realize the cascade recovery of the various exhaust heat in a comprehensive way on board, lower costs and improve the efficiency.

Acknowledgement

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