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Exploitation of Waste Heat of Marine Diesel Engines using Seebeck Elements

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ABSTRACT: In the last decade, thermoelectric element technology has bloomed, enabling Seebeck Element Thermoelectric Power Generators (hereafter: “TEGs”) to be used as significant alternative power sources, in several applications. Hence, thermoelectric elements started being introduced in the industry in fields other than their traditional use as temperature sensors. However, the broad use of Thermoelectric Elements was restricted in marine applications although plenty of unexploited energy is wasted in the form of exhaust gases heat losses. All attempts to use TEGs in vessels so far have been restricted because of the inevitable need for heat sinking. That was attempted mainly by transferring a cooling media (most often seawater) to the TEGs, which needed power-consuming pumping units practically eliminating the benefits of the recovered energy. This article describes the results of a research on a new technology for the production of Electrical Power on ships using TEG arrays cladded on the inner part of the vessel’s hull, always below the waterline. The steel plates of the vessel’s hull, when below the waterline (hereafter: “wet plates”), are in permanent contact with the seawater hence maintaining a constant low temperature on their inner side pretty close to the temperature of the seawater being on their other side, thus providing the necessary temperature gradient needed for the TEG efficient operation. Exhaust gases from the Main Propulsion or Electrical Generator Engines or ancillary equipment such as the vessel’s burners, incinerators, etc. are fed to the TEGs formed in arrays. The DC power produced is fed either to the vessel’s AC grid after DC/AC inverting, or in the form of DC serving the Vessel’s DC loads. All experimental and modeling results have shown that the overall power produced could lead to severe cuts in fossil fuel consumption and at the same time to a significant reduction of the environmental impact of maritime transportation. Understanding the basics of Thermoelectric Theory is a prerequisite for reading this article. The research on this new technology is the subject of the author’s Ph.D. research and at its early stages was first presented by the author at the ESTS 2019 International Conference, Washington USA. This article presents and comments on the results of this research now concluded, hence references to the initial publication of the innovation are necessary for the reader and duly marked in the reference sector of this article. The international patent of the innovation is pending.

KEYWORDS & KEY PHRASES: Marine fuel, Environmental impact, Exhaust gases, Cleaner Energy, Seebeck elements, TEG, Waste heat recovery, Wet steel plates.

I. INTRODUCTION

It is historically proven that every political, military, or economic crisis causes an increase in fuel prices which in many cases has been proven drastic. This reflects an avalanche of side effects with the rise of sea transportation costs to be the worst among them. As Maritime transport is the backbone of international trade this affects the prices of products and services globally. Around 80 percent of global trade by volume and over 70 percent of global trade by value are carried by sea and are handled by ports worldwide [1]. Hence, the international interest in developing more efficient ways to manage marine fuel costs became an International priority.

However, the need for a changed attitude towards the use of fossil fuel became a necessity during the '90s when the first serious effects of environmental pollution were too big to be ignored anymore. This was reflected in a change of the relevant legislation at both national and international levels. [2] [3].

As both the need for massive sea transportation and public environmental concerns grew rapidly over the years, the large marine internal combustion engines (hereafter: “ICE”) manufacturers' concern for building more effective engines became frantic. The need for fuel-saving became a win-win case, between the Ship Operators and the Environmental Organizations. It was in the early '90s when the discussion for alternative fuels [4] (LNG, Biodiesel, even Synthetic Coal) got into the picture, [5]. Yet the need for the reduction of consumption of traditional fuels (eg. HFO, MDO, etc) remained constant and imminent as this would require far fewer interventions in existing ICEs and consequently fewer costs and downtimes.

In this article, the results of a Ph.D. research are presented [6]. The scope of the research was to explore the feasibility of large-scale installation of Thermoelectric Generator modules (hereafter “TEG”) arrays in marine applications. As TEG technology is rapidly improving [7] a wider use of TEG module should be expected in marine applications yet this was so far restricted by the need of cooling facilities demanding power for pumping cooling sea-water. The research examined an innovation introducing the direct cooling of the TEG modules by conduction if they are in contact with the inner side of the wet steel plates of the ship's hull below the waterline. The TEGs arranged in arrays would have their hot sides attached to a ducting system conveying exhaust gases hence supplying the necessary thermal power. As the steel plates below the waterline have always a significantly lower temperature than the ambient due to the seawater on their outer side, therefore the cooling of the TEGs cold side would be direct, sufficient, and reliable. In this case, there would be no need for pumping units or the use of heat exchangers that would decrease the overall power factor of the system. The System performance is -almost linearly- improving proportionally with the speed of the vessel hence the velocity of the seawater in contact with the wet steel plates, and inversely proportionally to the seawater temperature. The innovation is explained in this paper. Modeling and experimental dynamic analyses are presented to define the benefits and possible drawbacks of the System, while certain issues and considerations (e.g. the possible build-up of backpressure higher than the one indicated by the Engine's manufacturer or the prevention of forming acid drops within the ducts) are also taken into account and discussed.

II. THERMODYNAMIC FIGURES OF MODERN MERCHANT MARINE TRANSPORTATION

A. Typical thermal equipment of a modern, newbuilt Ship

This research was based on a real life, newbuilt (2017) Bulk Carrier of 61000 Tons DWT. The ship's main propulsion system is an HYUNDAI – B&W 7G50ME-B9.3 (TIER II) ICE, with a nominal power rating of 12,040 KW @ 100 rpm supplying the propeller shaft with 1149820 Nm of torque giving the fully loaded ship a maximum speed of 18 Knots. The ship's Power Supply System (hereafter “PSS”) consists of a set of three HYUNDAI HIMSEN / 5H21/32 generators of 800 KW @ 720 RPM each. Two out of the three generators cover approximately 120% of the Ship's full load requirements under normal operational conditions. The vessel is not equipped with a shaft generator. Other thermal engines and ancillaries useful in supplying otherwise wasted energy are the SAACKE made, CMB-VS-1.6+0.5 +2x0.135/7 Composite Marine Boiler, and the Maxi NG 150 SL WS Incinerator made by HYUNDAI ATLAS. The ship's emergency Generator does not affect the installation or the performance of the System and will not be discussed.

B. Average Fuel Consumption

When the vessel sails at its engine's maximum continuous power rating (MCR), the fuel consumption is 162,5 g/KWh \pm 5% which makes an average of 1,5 tons of HFO per hour of journey. The engine's maximum continuous rating is 8860 KW @ 91,9 RPM providing 920707 Nm of torque to the shaft, driving a single 4 blade fixed pitch (5404mm) propeller, of 7 meters diameter, making the ship sail at 14.3 Knots, fully loaded. When at sea, two out of three main generators are in operation. Each of these generators has an average consumption of 185g/KWh +5% which leads to a total consumption of another 0,3 tons of fuel per operating hour. It has to be noticed that this latter consumption is still to be considered when the ship is not at sea but also in anchorage or docked without shore power supply. The daily fuel consumption of the Boiler burner which is approx. 1.2 tons per day when the ship is at anchorage or when the main engine does not operate in full load, has also to be added to the above.

Fig.1 depicts the distribution of power consumption in a modern marine ICE. Two-stroke, low-speed marine ICEs are the most efficient high-power engines manufactured so far, yet only 48 to 50% end up as useful shaft power [8].

Typical 2 stroke Marine Engine Energy distribution

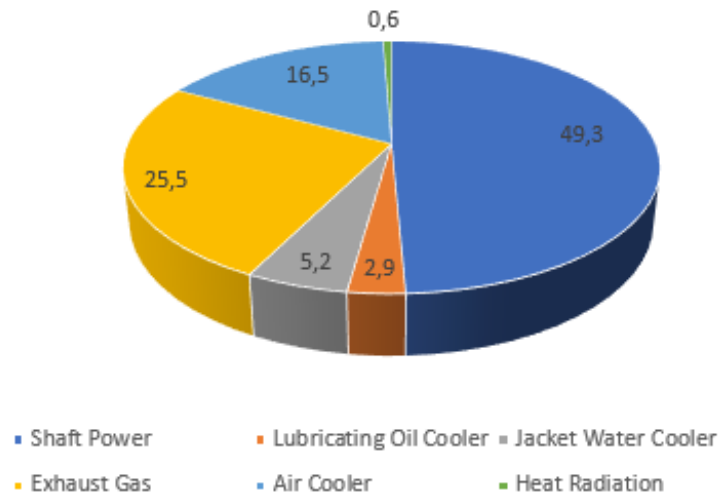


Fig. 1 Typical 2 stroke marine engine Energy distribution

C. The need for Waste Energy recovery in marine transportation

Since the early '80s, drastic climate changes have shown the way for increased research into alternative sources of energy [9]. Those rapid, already present, and imminent climate changes are greatly attributed to the use of fossil fuels for marine transportation [10]. Apart from the high environmental impact of marine transportation, shore activities related to maritime actions are also to be considered in the evaluation of the overall ecological footprint of shipping. Hence, many countries of the so-called developed world have been committed to the rationalization of energy consumption and the development of technologies and practices towards waste heat recovery. The U.S. Energy Administration in 2011 estimated that almost two-thirds of the total demand for petroleum is from the transportation sector [11]. With the assumption that the daily extraction and processing of oil is currently about 63.5 million barrels, global oil reserves are normally predicted to last not more than fifty years. In the average Western industry, 75% of the final energy is used for thermal uses such as burners, incinerators, boilers, and dryers. It is important to notice that around 30% of this heat is assumed to be wasted in the form of discharged hot exhaust gas, cooling water, and heated products. Hence, the recovery and re-utilization of waste heat are believed to contribute considerable amounts of energy to the energy needs of human activities.

Although energy-related Greenhouse Gases (GHG) emissions from fossil fuel combustion account for 70% of total emissions including those coming from heating and electricity generation, a relatively large portion is generated from the transportation industry [12]. Although alternative fuel (i.e. LNG, methanol, even electric) ships (ES) powered by renewable energies are seen as a possible future solution to reduce GHG from the sea transport industry, TEG technology might be also introduced to extract waste energy from several points of a ship's power generating or propulsion system. Still, two-stroke turbocharged, low-speed diesel engines, are the most commonly used marine propulsion systems nowadays. These engines are the most efficient, exhibiting approx. 50% efficiency, with the remaining 50% of the energy released from fuel combustion being dispelled to the atmosphere as waste heat [13]. Hence, a new energy-harvesting system that recovers this heat energy to convert it into electricity with the use of TEGs has been being studied and the results are introduced herein.

D. Marine turn to electrification and renewables

Developments that emerged recently in ship electrification show that more efficient use of energy is both necessary and possible. Sustainable power production can be used to produce electricity in order to power ships at berth or to charge batteries for fully electric and hybrid ships [14]. Expanding the role of electricity on ships will contribute towards improved energy management and fuel efficiency on larger vessels. Recent studies and real-life applications show that shifting from AC to onboard DC grids would allow generator driving engines to operate at variable speeds, helping to reduce energy losses [15]. The same could apply to large Vessels equipped with shaft generators, now limited to be used only when the main engine

runs at its MCR speed. Further benefits would be power oversupply and noise and vibration reduction, which is particularly significant for passenger ferries and cruisers. Efficient energy storage devices are of paramount importance for the propulsion of purely electrical ships [16], while they are also important for optimization of the use of energy on board in hybrid ships [17]. There are a variety of energy storage systems on the market nowadays. The most popular propulsion technologies are battery-powered, and smaller ships are currently being designed with them. Engine manufacturers are focused on hybrid battery systems for larger vessels. To ensure that battery-powered boats are competitive with traditional ones, challenges related to safety, availability of materials employed, and lifetime issues must be overcome, although technology is quickly progressing. Flywheels, supercapacitors, even thermal energy storage devices are some of the other energy storage technologies that could be used in transportation in the future. Electrification has sparked a lot of interest, especially among ship types that have a lot of load changes. In the coming years, significant expansion in hybrid ships such as port tugs, offshore service vessels, and passenger ships and cruises is projected [18]. TE Generation is likely to play an important part in this.

E. The TEGs in Marine Waste Heat recovery

The fundamental challenge with the TE generation is the effective cooling of the "cold" side of the module rather than obtaining the necessary heat on the "hot" side, as everyone familiar with the technology knows. Failure to do so will result in the module's near-immediate annihilation. This is the primary reason why TEG technology has not yet been widely adopted for marine applications. Several variants have lately been launched with little success due to the general practice of pumping cold seawater inside the ship and feeding it to heat exchangers where the modules were attached, resulting in a very poor overall power factor of the entire application. In this work, the modules forming TEG arrays have their hot side attached to ducts through which the exhaust gases are circulating. The modules' cold side is firmly and thermally coupled to the inner side of the hull plates, and the ducts assembly is attached to the ship's hull plates below the waterline. The gas heat is sunk to the seawater through the hull plates via conduction. In the arrangement examined in this article, the hot side of the TEG modules arranged in arrays is attached to ducts via which exhaust gases are circulating. The modules' cold side is firmly and thermally coupled to the internal hull plate's surface, and the ducts are attached to the ship's hull plates below the waterline. The heat convected from the gases to the modules passes through the hull plates into the seawater.

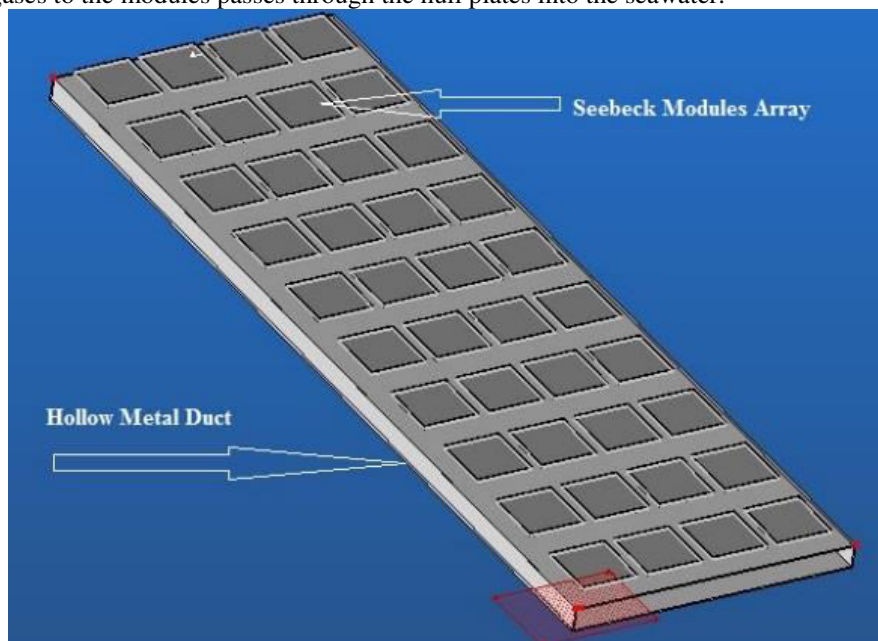


Fig.3 The TEG elements on exhaust gas duct forming the array [19]

The heat sinking is accomplished by firmly adhering the cold side of the modules below the waterline to the inner surface of the wet hull steel plates

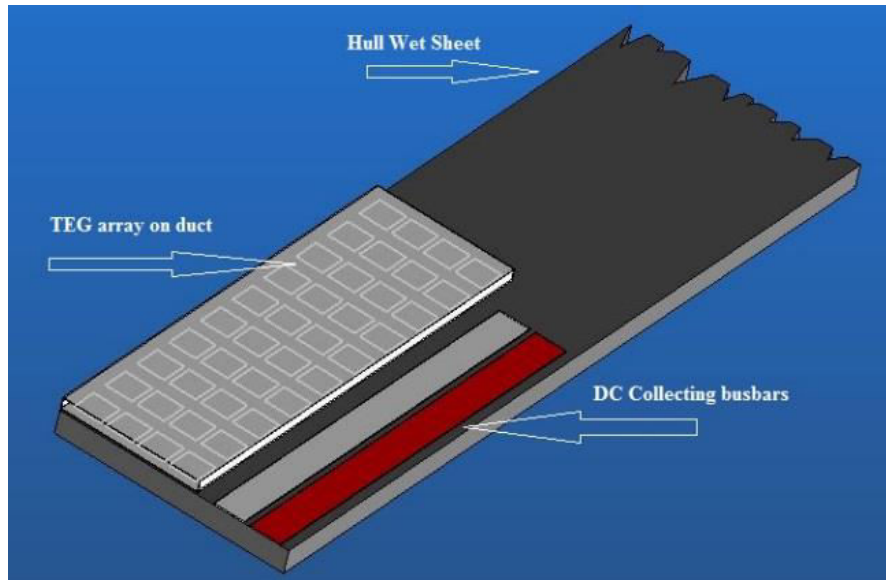


Fig.4 The array and the DC collecting bars attached to the hull wet plate. [20]

Seawater may be considered as an infinite heat sink hence cooling is simple to achieve, as model experiments have shown [21]. According to the formulae provided in the following paragraph, the efficiency of the system is inversely dependent on the temperature of the saltwater and directly dependent on the vessel's speed).

III. LITERATURE AND THEORY SURVE

F. Basic Theory and relations behind TEGs [22]

Thermoelectric energy generation is based on the Seebeck Effect which was discovered by Thomas Seebeck in early 1821. According to Seebeck's findings, an electromotive force appears when the two junctions forming an electrical circuit involving two different material conductors are kept in a Temperature difference ΔT . The voltage appearing between the junctions is directly proportional to the ΔT and Seebeck coefficient α , which depends on the nature of the materials, the purity, the volume, and the shape of the conductors. Although the effect occurs only when there is a junction between two materials, the Seebeck effect is a characteristic of the bulk rather than surface properties [23]. For many years the main practical application of the Seebeck effect was temperature measurement because the Seebeck coefficient was too small to produce significant voltages to be suitable for power applications. However, the rapid development of material chemistry has enabled the manufacturing of compact Seebeck effect arrays with considerable power output and efficiency, enabling their use in several practical applications involving mainly Energy harvesting [24].

The basic formulae used in TEG technology applications are as follows [25]:

The heat flow required on the element's hot side can be estimated as follows:

$$\dot{Q}_{hot} = \alpha(\hat{T}_{hot}) \cdot I \cdot \hat{T}_{hot} - \frac{\rho}{2} \cdot I^2 + \bar{k}(\hat{T}_{hot}) - \bar{T}_{(cold)} \quad (1)$$

while the voltage built-up at the element is:

$$U = \alpha(\bar{T}^{hot}) \cdot \bar{T}^{hot} - \alpha(\bar{T}^{cold}) \cdot \bar{T}^{cold} - \rho^- \cdot I \quad (2)$$

The element's electric power output is $P = I \cdot U$

The effective temperatures are calculated as follows:

$$\begin{aligned} T_{hot}^* &= T_{hot} - R_{th, hot} \cdot Q_{hot} \\ T_{cold}^* &= T_{cold} + R_{th, cold} \cdot (Q_{hot} - P) \end{aligned}$$

The electric resistance average value is:

$$\bar{\rho} = \frac{\int_{T_{Cold}^*}^{T_{Hot}} \frac{\rho(T)}{\kappa(T)} dT}{\int_{T_{Cold}^*}^{T_{Hot}} \frac{1}{\kappa(T)} dT} \quad (3)$$

The thermal conduction average value is:

$$\bar{\kappa} = \frac{\int_{T_{Cold}^*}^{T_{Hot}} \frac{1}{\kappa(T)^2} dT}{\int_{T_{Cold}^*}^{T_{Hot}} \frac{1}{\kappa(T)} dT} \quad (4)$$

The above expressions (1), (2), (3), and (4) describe the behavior of a typical TEG element. Symbols are explained as follows:

T_{hot} : applied absolute temperature on the hot side (heat source)

T_{hot}^* : hot side effective temperature

T_{cold} : cold side absolute temperature (heat dissipation)

T_{cold}^* : cold side effective temperature

$R_{th, hot}$: thermal resistance on the hot side (ceramic plate, thermal compound, etc.)

$R_{th, cold}$: thermal resistance on the cold side (ceramic plate, thermal compound, heat sink, etc.)

Q_{hot} : heat flow needed on the hot side

U : voltage generated

I : current flowing through the element

P : electric power supplied

$\alpha(T)$: thermal force (corrected)

$\rho(T)$: electric resistance (corrected)

$\kappa(T)$: thermal conduction (corrected)

$\bar{\rho}$: effective electric resistance

$\bar{\kappa}$: effective thermal conduction

G. TEG module selected

For the testing part of the research, the TEHP1-12656-0.3 made by IEH was selected. The continuous development of the TEG technology has made available many TEG chips ever since, with improved characteristics compared to the one used in this research. Nevertheless, the chip used has the following characteristics [26]:

- Hot Side Temperature (°C) 300 (average)
- Cold Side Temperature (°C) 30 (average)
- Open Circuit Voltage (V) 8.4
- Matched Load Resistance (ohms) 0.9
- Matched load output voltage (V) 4.2
- Matched load output current (A) 4.6
- Matched load output power (W) 19.3

- Heat flow across the module(W) ≈ 306
- AC Resistance (ohms) Measured under 27 °C @ 1000 Hz 0.25 ~ 0.4

The element is a high-efficiency thermoelectric module, based on Bismuth -Tellurite technology, that can work constantly at 330 degrees Celsius (626 degrees Fahrenheit) and intermittently up to 400 degrees Celsius (752 degrees Fahrenheit). As long as there is a temperature difference across the module, the thermoelectric module will generate DC electricity proportional to the temperature gradient between its sides. When the temperature difference across the module increases, more power is generated, and the efficiency of turning thermal energy into electricity increases practically linearly. Because the module is sandwiched between two high thermal conductivity graphite sheets on both sides of the ceramic plates to provide low contact thermal resistance, manufacturers suggest that no thermal gel or other heat transfer compound is necessary during installation.

The following graph depicts the overall performance of the specific module:

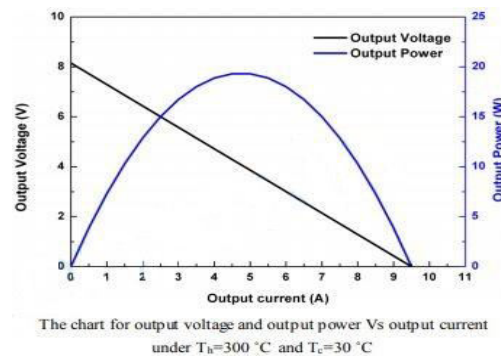


Fig.5 Voltage vs Current curve of the TEHP1-12656-0.3 module

The produced voltage lowers to 4 Volts at 5 Amps of current, according to the producers, and the module produces its maximum power of 20 Watts.

The following diagram provided by the module manufacturer depicts the Power produced vs the T_c (Temperature gradient)

Given that the inner side of the wet hull metal plates below the waterline is virtually always cooler than 30°, the module's performance should be improving as the $\Delta\theta$ increases.

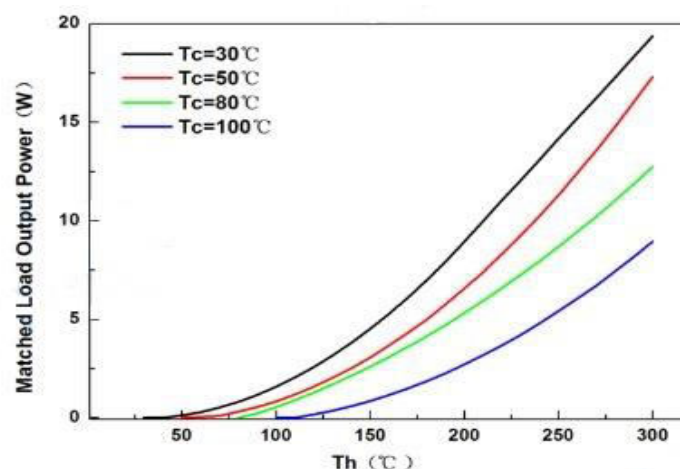


Fig.6 Output Power Vs Temp. curve of the TEHP1-12656-0.3

H. Cooling procedure simulation

As already discussed in the introduction, the idea is that the cooling of the TEG modules will be done by attaching the arrays and the array bearing exhaust gas duct directly to the always cooler metal plates of the sea hull below the waterline and hence to achieve full heat sinking by direct conduction.

- I. The hull components that have a direct touch with the seawater on their outside side are referred to as "wet metal plates" in shipyard language. Several stiffeners, girders, beams, pillars, and other structural elements support these plates from the inside, depending on the naval architecture of each specific vessel. The free area between these structural components on the plates is ideal for attaching TEG module arrays. Special attention should be paid to the fact that the arrays are always situated below the ship's Lower Water Line (hereinafter "LWL").

The wet metal plates that make up the hull of the ship in issue are built of ASTM A131 Part 4 high strength structural shipbuilding steel, with thicknesses ranging from 12 to 16 mm.

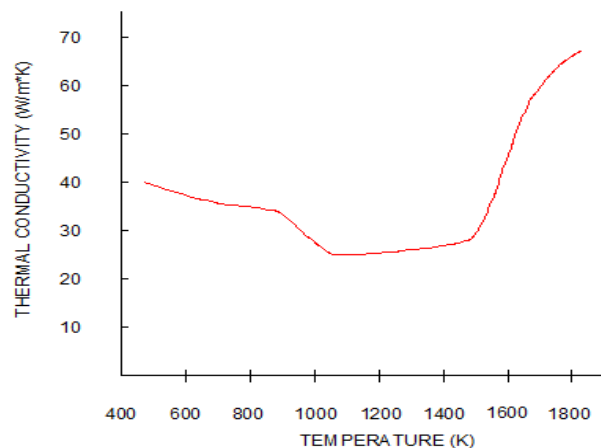


Fig.7 Thermal Conductivity vsTemperature of AH36 structural steel

The ANSYS® FEA Software has been used to simulate heat transmission from the duct system bearing the TEG arrays to the hull plate and from there to the sea. This ensured that the heat generated by the array was properly sunk.

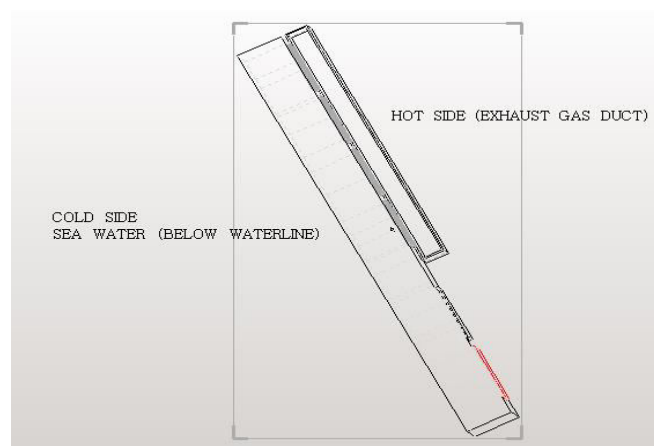


Fig. 8 Schematic of the assembly attached on the ship's Hull []

IV. EXPERIMENTAL PROCEDURE AND RESULTS

As part of the relevant Ph.D. research, several simulations both practical and using computers have been done. A basic but enlightening experiment is presented in this paper. The simulation took place in the Salamis Vocational Lyceum Lab Centre's Marine Engines Lab on Salamis Island, Greece.

A used Perkins-Sabre M92B, 4 Cyl, 4.4 liters, direct injection, natural aspiration Marine Engine from an old fishing boat generated the exhaust emissions. The engine's maximum torque is 308Nm at 1200 rpm, and its rated power is 64KW at 2400 rpm. For thermal stabilization (1st phase), the engine was run at idle speed with no load for thirty minutes, then increased to 1100 rpm for another 15 minutes (2nd phase). At the 2nd phase, the gas temperature was measured at the exhaust and determined to be 240-265° C.

The array consisted of 20 TE HP1-12656-0.3 TEG Modules mounted on a 250x300x50 mm hollow exhaust duct. A thin layer application of EHTS10K Electrolube® Silicone Heat Transfer paste was necessary mainly to smoothen surface imperfections of the marine structural steel used to imitate the wet plate. The modules were arranged in a 4x5 grid, with two pairs connected in series and one pair connected in parallel.

As illustrated in Fig. 8 & 9, the entire structure was clamped on a piece of marine structural steel with a thickness of 12 mm, simulating the ship's hull wet plate.

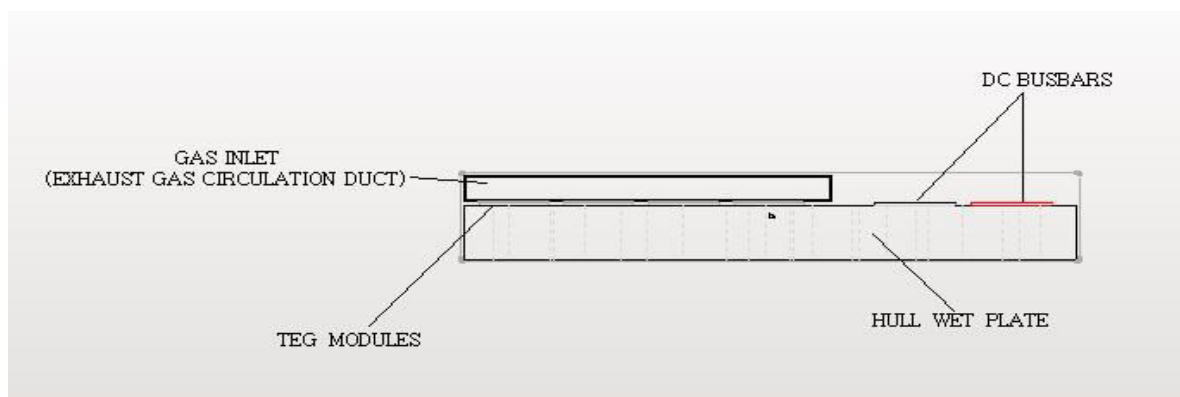


Fig.9 Cross-Sectional cut of the TEG array assembly attached to the Hull plate.

The wet plate was in touch with running (fresh) water to simulate seawater flowing at the opposite velocity of the ship's movement, gradually lowering the temperature of the outer side of the hull plate from 100°C to 30°C.

The following is the open-circuit voltage versus cold side temperature table:

CS temp. (°C)		Pair Voltage (V)
100		8,4
90		9,1
80		10,2
70		11
60		11,6
50		12
40		12,6
30		13,9

depicted by the following graph:

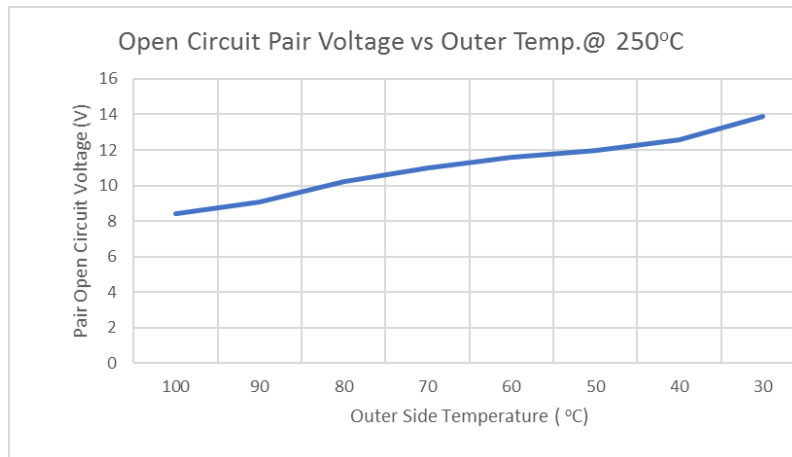


Fig.10: Open circuit voltage vs cold side temperature

HS temp. (°C)	CS temp. (°C)	$\Delta\theta$ (°C)	Pair Voltage (V)
50	20	30	0
100	22	78	4,61
150	25	125	7,39
200	27	173	10,23
250	29	221	13,07
265	30	235	13,9

The open-circuit voltage vs the $\Delta\theta$ curve follows:

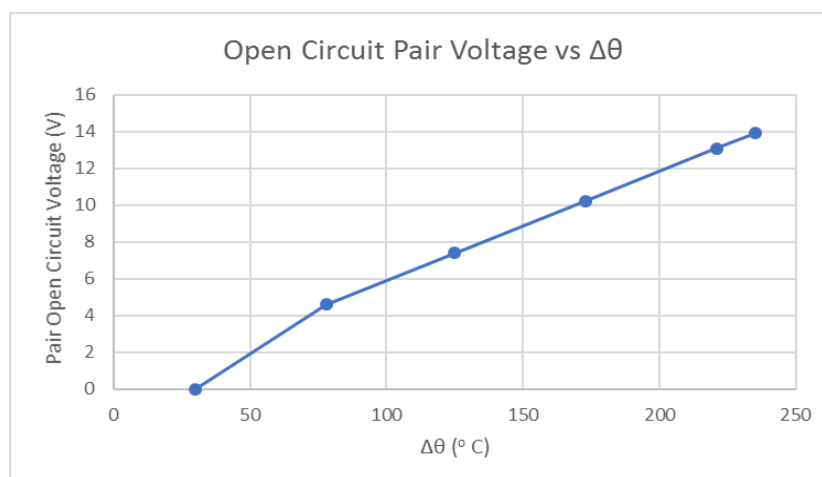


Fig.11: Open circuit voltage vs the $\Delta\theta$

In the second stage of the experiment, the array was electrically connected to a changeable and deliberately mismatched load with pure Ohmic behavior in the form of a DC Motor resistance starting. The results are listed in the table below:

Voltage (V)	Current (A)	Ohmic Load (Ω)
14	1	14,00
12,2	2	6,10
11	3	3,67
10	4	2,50
8	5	1,60
6	6	1,00
5	7	0,71
3	8	0,38
1	9	0,11
0	9,5	0,00

hence producing the following graph:

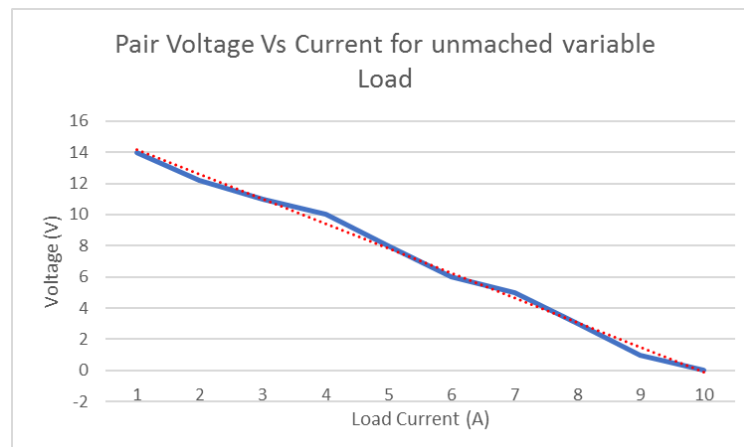


Fig.12:Module pair Voltage vs Current for unmatched variable load

From a first observation of the results, a very promising behavior of the system was derived, as the Voltage vs Current curve was found to be almost linear [27].

V. MODELLING-SIMULATION

The implementation of a trial installation on a real-life scale system onboard a vessel was impossible at this stage of the research due to safety, documentation, approval, and insurance reasons [28]. Therefore, modeling and FEA simulations would be the only practical means for the initial estimation of possible benefits and drawbacks of the innovation proposed. A MATLAB®SIMULINK® model was created and fed with all manufacturing and performance data of the selected TEG module. The very promising results will be discussed in Section D of this chapter.

J. Issues considered

a.1 Matching the load.

A TEG array with modules connected in series and module groups connected in parallel delivers the most power when coupled to a load of equal impedance as its own. [29] When it comes to real-life applications, though, this isn't always achievable, and it's seldom the case. Special electronic devices are currently used to regulate circuit parameters so that the load impedance is always as close to one of the arrays as possible. [30]

$$V_{\alpha} = \frac{N_l}{2} \cdot a \cdot \Delta T$$

A DC is created when a load is connected between the module terminals in the presence of a temperature difference between its sides. As from any other linear DC Voltage source, the current delivered by the TEG module may be calculated using Ohm's law on its equivalent circuit, which consists of a DC Source (V_a) and a resistance (R_{int}) in series with the Load (R_{load}). The current is inversely proportional to the load value, as is the power given to the load, according to Ohm's law. When a load is connected between the module terminals while a temperature difference exists between its sides, a DC is formed. The current produced by the TEG module may be estimated using Ohm's law on its equivalent circuit, which consists of a DC Source (V_a) and a resistance (R_{int}) in series with the load (R_{load}), just like any other linear DC Voltage source. The current, as well as the power provided to the load, is inversely proportional to the load value, according to Ohm's law.

$$I = \frac{V_a}{R_{int} + R_{load}}$$

The resistance factor R_{int} stands for the module's internal resistance, which is determined using the equation below, where σ is the electrical conductivity of the thermoelectric material.

$$R_{int} = N_l \cdot \frac{L_l}{A_l + \sigma}$$

where N_l is the number of thermoelectric pellets, L_l is their length, and A_l is their cross-sectional area. When a load is attached, the voltage delivered to the load is lower than V_a because of the module thermal resistance. The greatest power transmission occurs when the load equals the module's resistance, under the Maximum Power Transfer Theorem. Another use option would be to use the electricity provided by the arrays to charge batteries, as batteries use is expected to expand in the near future [31]. However, as the resistance of the batteries changes with the increase of the charging level electronic regulators the monitoring of the load would still be required. A PLC model for the monitoring of the load and the power production during the physical simulation was developed and used during the physical simulation in the Laboratory mentioned in the previous sector.

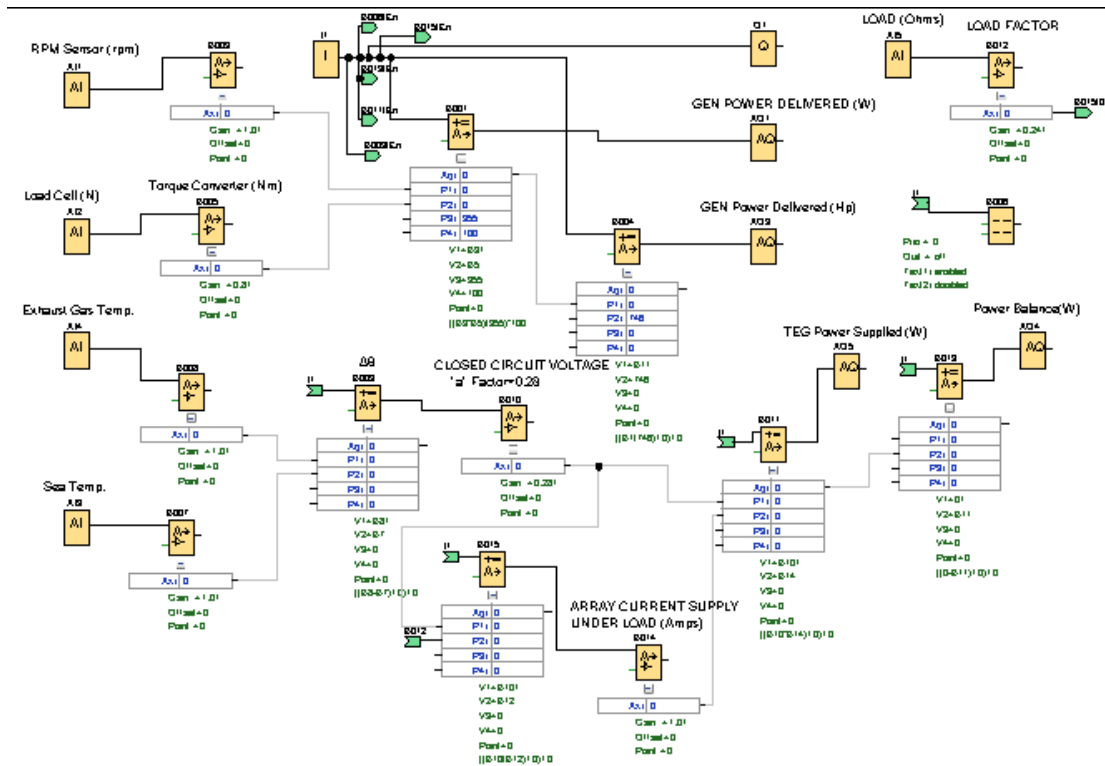


Figure 13: TEG Monitoring PLC program

a.2 Exhaust Gas Back Pressure.

The use of the system by retrofitting on an existing ship, as well as the construction of a new ship layout, necessitates the consideration of an inevitable increase in exhaust gas backpressure. Increased back pressure can lead to higher emissions and fuel consumption, as well as a reduction in engine performance. The pressure loss was expected to be significant and has been thoroughly researched due to the intricacy of the pipework for exhaust gas ducting the gases through the system. The following are some of the implications of increased exhaust pressure on a diesel engine [32]:

- Increased scavenging work
- Reduced intake manifold boost pressure
- Cylinder scavenging and combustion effects
- Turbocharger malfunction problems

Backpressure varies depending on the installation, hence a separate study for each case was conducted using both -models and CFD simulation. Because of the duct's straight-line shape and uniform cross-sectional area, backpressure was not measurable, and hence neglected in the initial simulation described above. Nevertheless, as the backpressure built-up should be thoroughly calculated before the implementation of the System to existing or newly built vessels, a CFD and FEA simulation should be run. To elaborate a uniform technique for evaluation of the impact of the geometry on velocity, temperature, and backpressure building for a basic module of each configuration, two primary duct arrangements (in series and parallel configuration) were investigated. Two sets of ducts with different geometry were designed and fed to the mathematical model. The ducts were redesigned using inox 316 L steel 1.5mm thick, having a thermal conductivity of 45 W/mK. The ducts were thermally insulated from all sides using a layer of thermal insulation of a total thermal conductivity of 0.8 W/mK except for the side in contact with the hull plates where the TEG arrays were attached. The exhaust gas initial streamline velocity, depicted in the following pictures shows that the backup pressure being built up can be significantly reduced by the application of several design improvements.

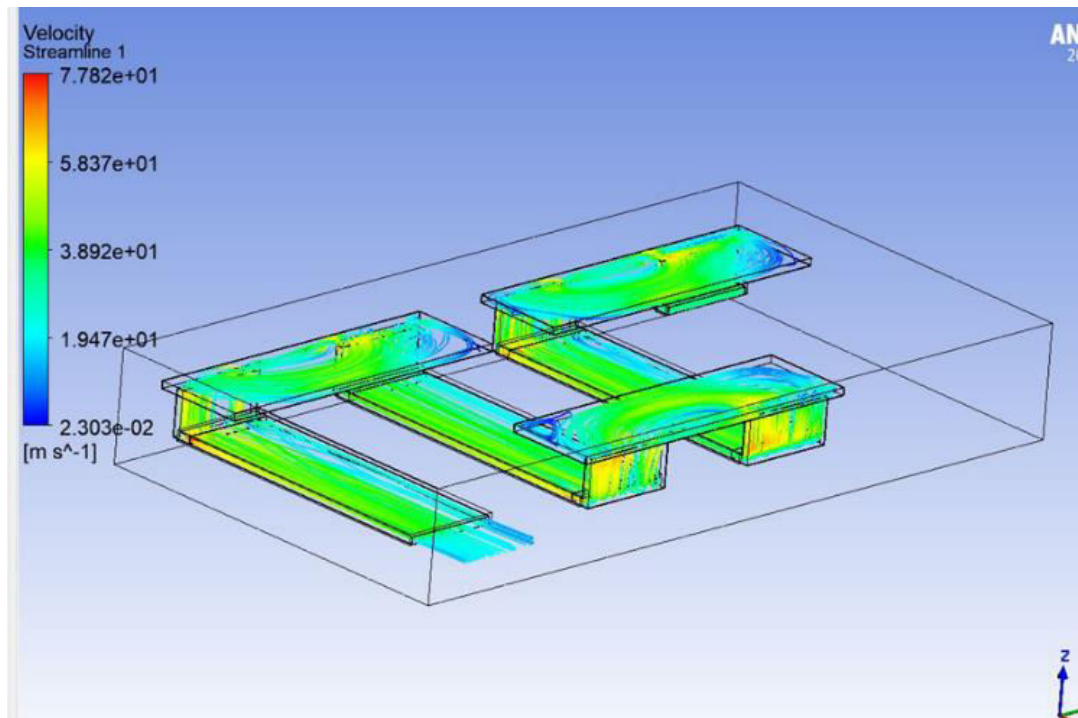


Figure 14: Basic module in Series configuration Gas velocity simulation

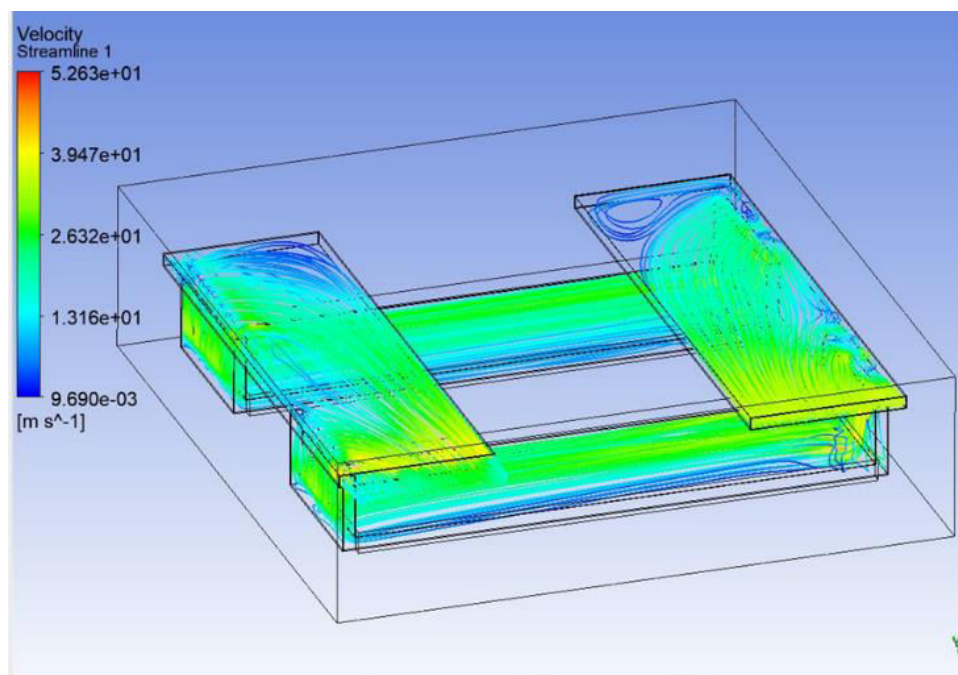
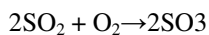


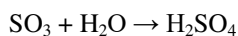
Figure 15: Basic module parallel configuration Gas velocity simulation

a.3 Exhaust Gas Dew Point.

A significant amount of waste heat in flue gases remains unexploited due to the limited applicability of metal heat ducts under conditions where acid dew point corrosion can occur. During the combustion of sulfur-bearing fuel with excess air, most of the sulfur is converted into gaseous SO_2 or is absorbed into particulate matter (PM) emissions. A small fraction is also converted into gaseous SO_3 . Sulfuric acid is primarily formed in diesel exhaust by a two-step process. In the first step gaseous SO_2 reacts with oxygen in the exhaust to form SO_3 which is described as follows:



The SO_3 subsequently reacts with moisture in the exhaust to form sulfuric acid according to the following reaction:



Sulfuric acid will condense near temperatures nearing 150°C under typical exhaust settings, while water will condense around temperatures near $25\text{--}30^\circ\text{C}$. [33]. Acid condensates should be avoided at any cost as they will inevitably cause severe wear in the ducting walls.

As a result of the above, a calculation of the heat absorption and thus temperature drop of the gases circulating in the duct system has been carried out using Finite Elements Analysis. The temperature drop of the exhaust gases was insignificant (less than 30°C) during the first simulations, owing to the short length of the ducting, with the exhaust gases temperature output much above the dewpoint.

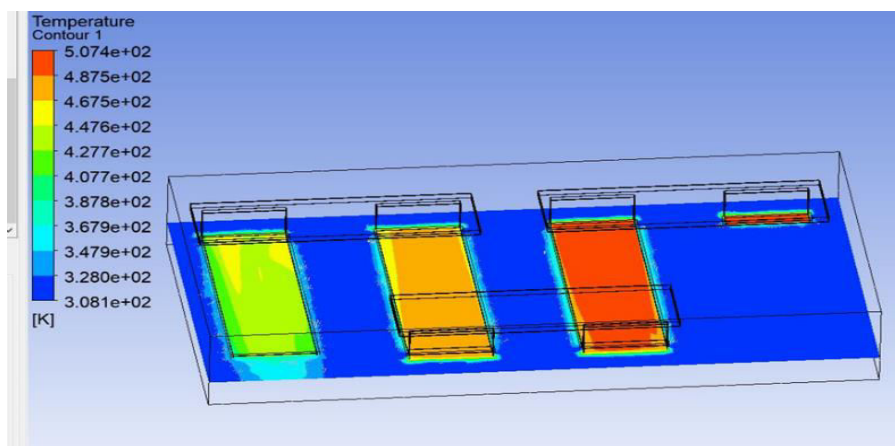


Figure 16: In series configuration basic module Temperature Drop simulation

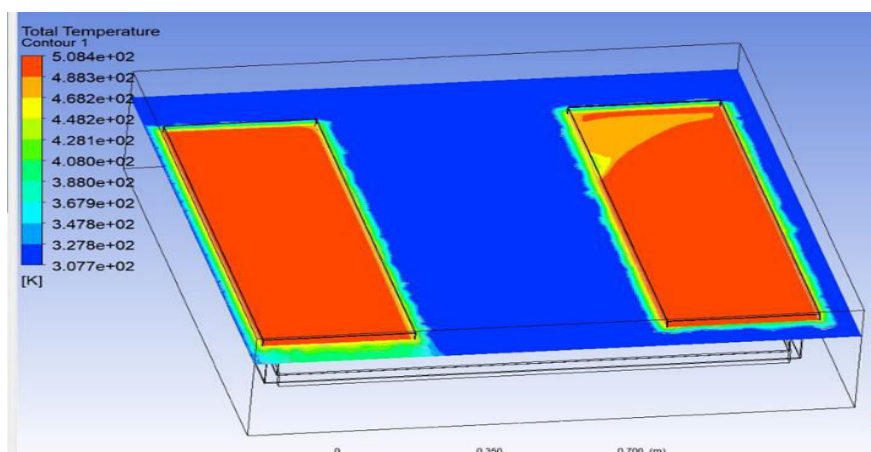


Figure 17: Basic module parallel configuration Temperature Drop simulation

Since the use of Exhaust Gas Cleaning Systems (EGCS) has been made obligatory by the IMO [34], the retrofitting of scrubber systems is a necessity. The use of Sodium hydroxide, also known as caustic soda used in the vast majority of scrubber systems is being examined as possible means offlashing media, to wash away exhaust gas residues in the TEG ducting system. The use of acidity and temperature monitors throughout the whole length of the ducting system will preserve that dew point condensates will not appear during operations and if they appear will be neutralized by an automatic Sodium Hydroxide solution flushing system.

However, because desulphurization is currently a strategic goal for the marine sector, it is reasonable to expect that the sulfur content of commercially utilized HFO and IFO will fall significantly in the near future. Despite the wide range of desulphurization methods mentioned in the literature, only a handful of them is now practical for the desulfurization of heavy oil. This is owing to the heavy oil's features, which include a high sulfur concentration, high viscosity, high boiling point, and the sulfur compounds' refractory nature [35].

a.4 Inverting to AC

The inversion of the DC power supplied by the arrays to AC is unavoidable because the great majority of the electrical loads on a modern ship operate on an AC source. The efficiency of modern inverters is well over 90%, however, this varies depending on the kind of load (resistive or inductive) and the inverter's standby current draw. The power loss due to inversion is a question that must be answered in each application separately, and it is still being calculated for the vessel described. It should be noted that the DC-generated electricity can be used directly to charge the Ship's batteries or to power sensitive electrical equipment.

VI. CONCLUSIONS

K. Discussion of the overall Results

The initial results have shown asignificantpercentage of waste heat recovery by using TEG arrays cooled by thehull plates of the ship, below the waterline. The average power amount produced was a very promising 12W per module for an unmatched load. The closest possible appreciation of the percentage of the waste heat recovery is still being investigated both by experimental and simulating methodsusing Finite Elements Analysis software and where impossible, by use of statistic methods and mathematical modeling evaluation approaches.

The results of the FEA analysis have been fed to a MATLAB® SIMULINK® model developed for this reason. The model has then fed with indicative data from a typical six months trip of the vessel mentioned in chapter 1. The data included average daily seawater temperature, the average inner wet sheet temperature, the average vessel's speed, etc. The model then calculated the average power generated by and an only array of TEGs installed on the ship's hull, consisting of 270 Seebeck chips for a near matched (and not perfectly matched load which will be the case in most cases).

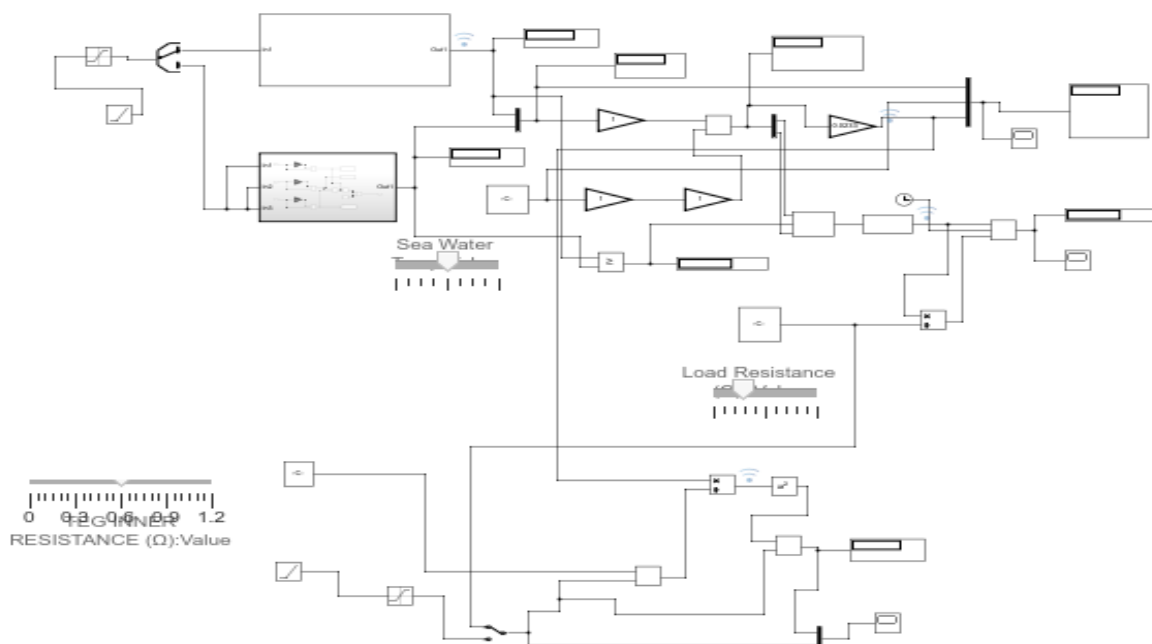


Figure 17: General Graphic overview of the model

SUMMARY OF THE CONCLUSIONS

Observing the simulation results, one could make the following remarks:

Examining a common typical trip from China to the North West of the USA the model showed that the minimum power supplied per chip was 14,24W when the ship sailed in the warmer waters of the China Sea, to rise to 14,97W when she finished her journey at the colder waters of the North Pacific. Hence the total power supplied by the 1 m² array would be 3844,54 W to 4041,38W, thus supplying the ship with 92,27 KWh to 96,39KWh per day.

Adding up the energy quantities supplied by the array to the vessel's grid the whole 22 days of the journey, the amount sums up to 2080,38 KWh/m². Running the same model simulation for the whole six months journey (109 days at sea), the total energy capability per m² of Seebeck arrays yielded a sum of 13589,33 KWh. The Total quantity of Fuel saved per 6 months trip per m² of TEG arrays: 2582 Kg (Calculation based on the Hyundai-Himsen H21/32 @ 900rpm, fuel consumption 190 g/KWh, charged in nominal power). And this was the energy offered by a single 1m² of arrays.

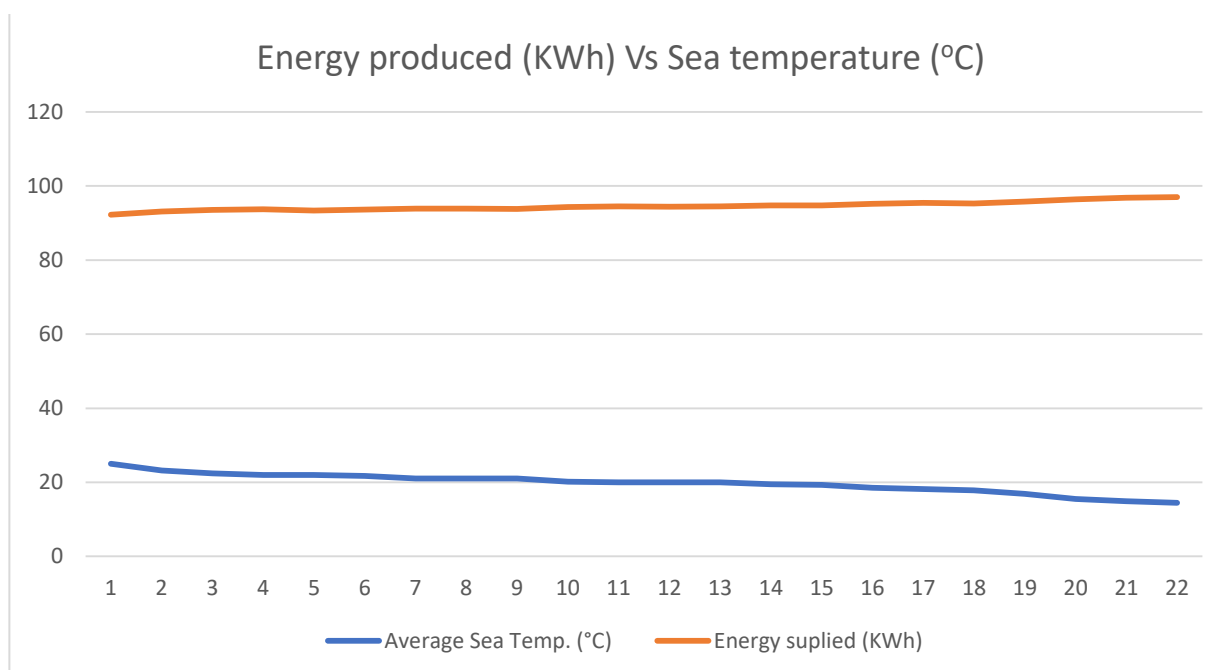


Figure 18: Energy supplied by TEG System during a 21 day Journey

Broadening the study to a typical six months period journey of the ship in question, with the vessel calling to six of its usual international ports, the sea temperatures were observed and the wet plates' inner temperatures were measured. The graph below shows the actual temperature differences between seawater and the cooling surface of the inner plates, where the heatsinking of the plates takes place and is typical for a part of the journey.

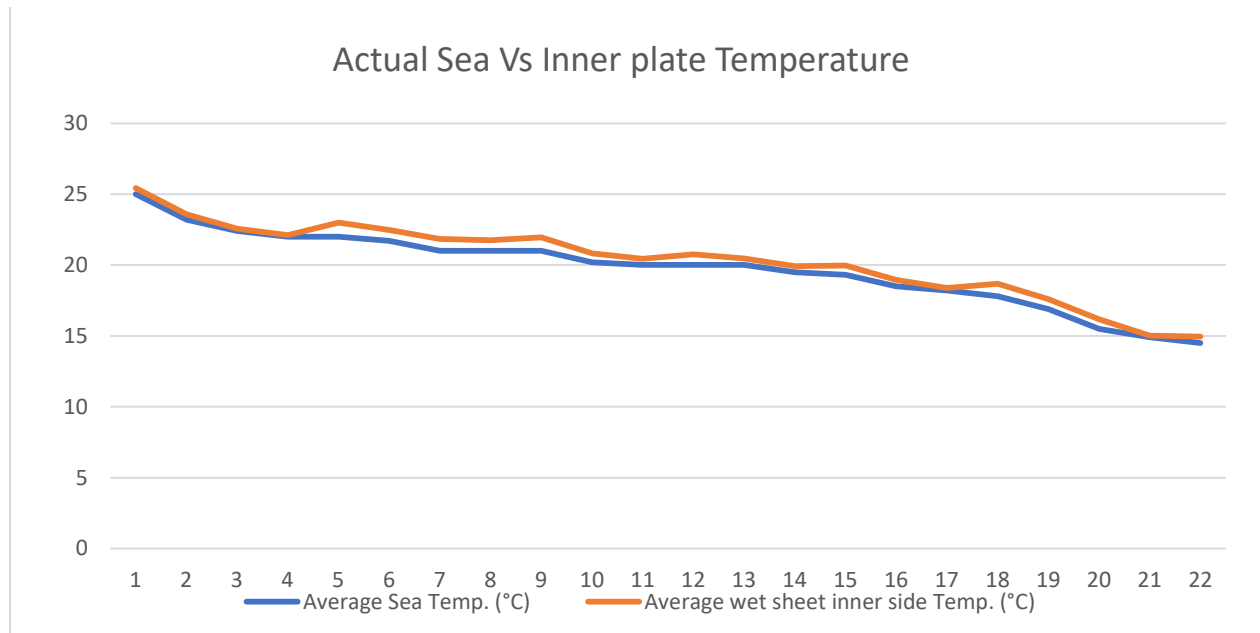


Figure 19:Temperature difference between Seawater and Heat Sink Plates

The data were fed into the Model, and the results were estimated for six months (109 days at sea): Total Energy Capability per m^2 : 13589,33 KWh. The total quantity of Fuel saved per 6 months trip per m^2 of TEG arrays: 2582 Kg (Calculation based on the Hyundai-Himsen H21/32 @ 900rpm, fuel consumption 190 g/KWh, charged in nominal power). The following chart shows the fluctuation of the energy production Vs the Sea Temperature for the whole duration of the 6 months. It has to be noticed that the System was considered to be out of duty during the stay of the ships at port or when the main engine was off duty.

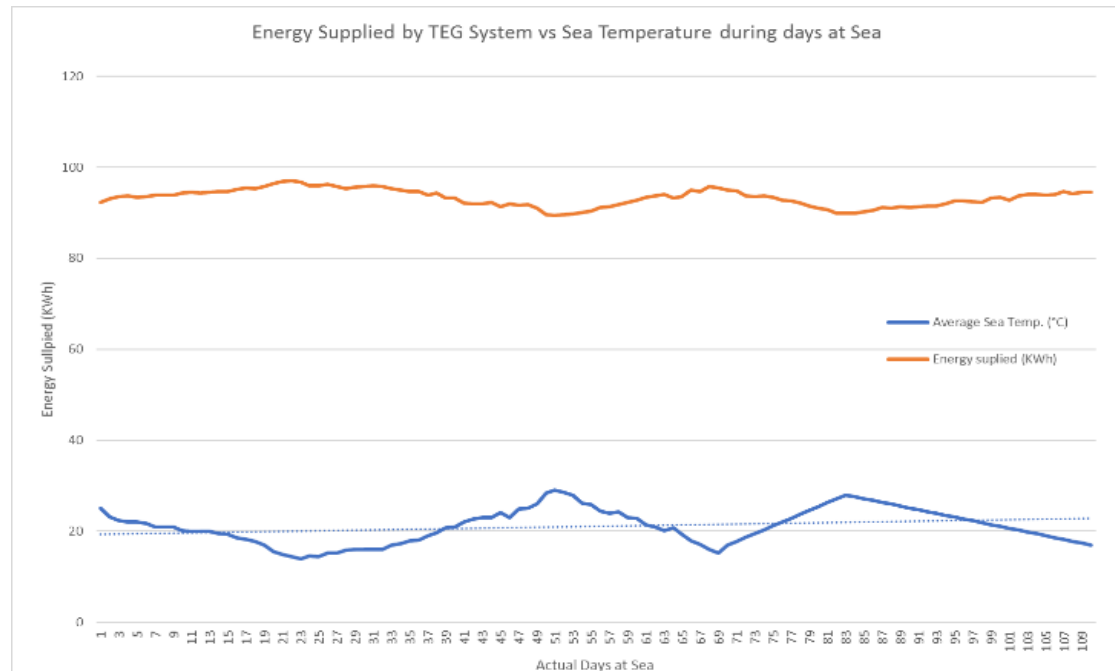


Figure 20: Energy Supplied by the TEG System Vs Sea Temperature

Bearing in mind that the future trend in maritime transportation is definitely oriented to drastically reduce the use of fossil fuel, the use of all means for fuel saving is a necessity. An increase of 10% in the efficiency of marine propulsion and onboard power generation engines will decrease the oil consumption per 180000 barrels of fuel per day [36]. The first very promising results show that if this new technology would be used on a large scale could lead to a drastic cut of the ship's power-generating fuel consumption decreasing accordingly the ship's ecological footprint and the overall marine transportation costs.

The research on this new technology is currently being finalized by statistical hypotheses testings at the Cyprus University of Technology, while the international patent is pending.

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