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A modular dynamic mathematical model of thermoelectric elements for marine applications

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ABSTRACT

This paper presents a modular, dynamic and spatially distributed model of thermoelectric elements for marine applications intended to assess the low-grade waste heat recovery potential of thermoelectric devices on-board seagoing vessels. The model describes the dynamic behaviour of marine thermoelectric components and captures the detailed thermodynamic and thermoelectric process phenomena. Validation against experimental data from the literature indicates good model predictive ability. Two marine applications are examined using the model: (a) a scavenge air cooler, and (b) an auxiliary engine exhaust gas duct section integrated with thermoelectric generators. For each case, a parametric analysis is conducted to identify the designs that yield maximum thermoelectric efficiency and power output. The study concludes that thermoelectrics can recover low-grade waste heat on-board ships. Systems engineering modelling and simulation techniques can successfully determine the best system design, to achieve maximum energy harvesting, satisfying the weight, space and operational constraints on-board.

1. Introduction

This paper presents a validated modular dynamic mathematical model of thermoelectric elements for marine applications, aiming to analyse possible energy harvesting benefits from using thermoelectric technologies on-board seagoing vessels. Energy efficiency concerns and environmental legislation drive the shipping industry towards the examination of novel technologies that could improve ship's environmental footprint and fuel economy. New technology solutions are explored, including, among others, new/alternative fuels, fuel cells, waste heat recovery options, hybrid-electric and next-generation propulsion systems, innovative cargo handling mechanisms, information and communication technologies [1]. A state-of-the-art method to cost-effectively explore alternative system designs and new technologies is via process modelling and simulation. Validated process models can offer insight into the governing process mechanisms and allow the analysis of system performance at steady-state and transient operation. In this context, model-based analysis of novel technologies like thermoelectrics can offer an essential level of understanding of the technology impact on vessel's efficiency, economy and environmental performance.

TEM (Thermoelectric modules) are solid-state energy conversion devices that convert heat to electricity and vice-versa due to the Seebeck and Peltier effects [2]. According to the Seebeck effect, a voltage difference is produced in the presence of temperature difference at the junctions of two pellets of different metal or semiconductor material. Peltier is a complementary effect, causing the absorption or emission of heat at the junction of two different conductors driven by an electric current. TEMs (Fig. 1) consist of arrays of THC (thermoelectric couples), each made of 2 pellets of dissimilar semiconductor material (n- and p-type), like Bi (bismuth) and Te (telluride) [2]. Semiconductors have balanced thermal and electrical properties, offering good thermoelectric behaviour. THCs are connected electrically in series via a conductor, like copper, and they are sandwiched between 2 ceramic substrates that offer rigidity and electric insulation. TEMs can operate either as TEG (generators) or TEC (coolers) on the principles of the Seebeck and Peltier effects, depending on whether heat is applied or an electric current.

TEGs are commonly used for powering of low-consumption devices, exploiting available temperature differentials. As needing no fuel supply, they offer a solution for isolated power supply and low-grade waste heat recovery, such as for wireless sensors,

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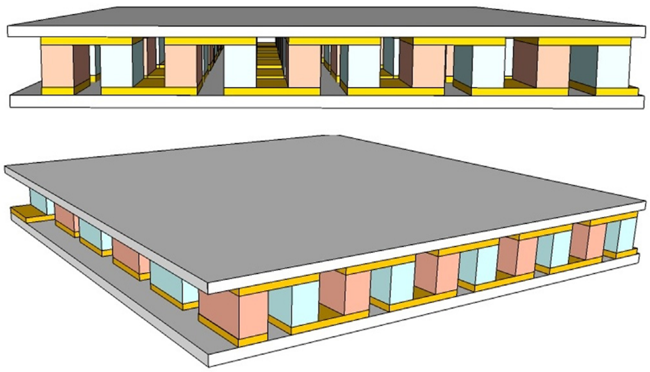

Fig. 1. Illustration of a TEM; the different semiconductor materials are shown with different colours. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

telecommunications, domestic use, space applications, and automobile prototypes [3–9]. Unlike conventional heat engines, TEGs contain no moving parts, leading to high durability, negligible maintenance needs and vibration-free operation. Despite their attractive advantages, commercial TEGs have limited power conversion efficiency at an order of 5–6%. Another disadvantage lies in their cost; prices are high varying per application area and depend on the power density requirements.

Regarding marine applications, TEGs have already received attention for waste heat recovery in conventional ship energy systems, because they are pollution-free, reliable, silent and easy-to-fit devices [10,11]. However, their implementation is still limited, due to the technology cost and the lack of a holistic approach to design such systems integrating them to existing ship components. Capital cost reduction would eventually come as a result of research and development, extensive testing and gradual commercial adoption of the technology.

In this paper, we present a phenomenological dynamic and spatially distributed model of marine process components incorporating TEGs. The model is modular encompassing 3 individual building blocks: (i) the TEG; (ii) a standard marine CHX (compact plate heat exchanger); and (iii) a duct. These blocks can be combined in different configurations to design and test a range of marine TEG applications. The model is validated against experimental and computational studies, to verify its results. The model is used to simulate 2 marine cases: (i) a scavenge air cooler with TEGs and (ii) an exhaust gas duct with TEGs. A number of studies are conducted per case, including design, part-load and transient analyses.

In Section 2, a review on state-of-the-art modelling and simulation works for thermoelectric applications is given. Section 3 presents the mathematical modelling of the TEG, the compact plate heat exchanger and the duct. In Section 4, the model validation is shown against simulation and experimental data from literature, at steady-state and transient conditions. Section 5 finally presents the TEG marine case studies and analyses the derived results.

2. Background

To improve TEG energy conversion efficiency, researchers have conducted a number of simulation studies using models of different levels of detail and assumptions, such as lumped flows, steady-state approaches, fixed TEG properties and simplified heat transport [12]. Hendricks and Lustbader [13] analysed an exhaust gas heat recovery system with TEGs for light- and heavy-duty road vehicles using a steady-state model that employed the ε-NTU (Number of Transfer Units) methodology to investigate the influence of heat exchanger design on the TEG power production. Bélanger and Gosselin [14] presented a steady-state 2D distributed model of a crossflow heat exchanger with TEGs that implemented the finite volume method to solve the model equations. The heat transport was simplified by applying an aggregated heat transfer coefficient for both convection and conduction. In Wang et al. [15], a steady-state numerical model with a finite element scheme is employed to predict the performance of a TEG combined with an air-cooling system and optimise the system geometry.

State-of-the-art thermoelectric models are capable of simulating the dynamic behaviour of TEG systems during thermal transient events. Montecucco et al. [16] analytically solved the unsteady heat conduction equation through a TEG, including internal Joule heating effect. The study showed that transient temperature events influence TEG thermal conduction properties, affecting Joule heat generation and temperature differentials. Lineykin and Ben-Yaakov [17] developed an equivalent-circuit dynamic model for a simple TEM configuration with solid wall surroundings. Their study showed that system dynamics were mainly influenced by the solid wall thermal resistances, whereas the assumption of stationary TEM behaviour was sufficient. Gou et al. [18] developed a dynamic TEG model to analyse the influence of hot and cold temperature transients on TEG power production. The configuration consisted of a hot flow channel surrounded by TEGs, which were cooled by a system of external finned heat exchangers and air fans. The model comprised a system of energy balance equations expressed at 2 distribution domains at the directions of (a) the hot channel flow and (b) the heat transport. Using the dynamic model, the unsteady response of the wall and semiconductor temperatures was studied at varying hot flow inlet conditions.

In the literature, few case-specific studies address TEG use onboard ships and there is no generic modelling approach to allow a wider exploration of marine applications. Chen et al. [10] combined a CFD model of a marine 300 kW boiler furnace with a multidimensional TEG model to analyse the system heat recovery potential. The TEG power production was estimated at more than 600 W for nominal boiler loading. Kristiansen et al. [11] estimated the performance of a marine waste incinerator with TEGs. The system design parameters were optimised for minimum TEG cost per unit of power produced and the maximum power gain was 58 kW at a price of 6.6 USD/W (in 2012 USD) from a marine incinerator of 850 kW capacity. The system required an extra cooling water network to maintain low temperature at the external TEG facets. To the authors' knowledge, there are no studies in literature that use process modelling and simulation techniques to explore the thermoelectric conversion potential in marine heat exchangers, where the abundance of seawater coolant in combination with high working fluid temperatures could provide an advantageous environment for TEGs.

Our model builds upon and extends past works on the modelling and simulation of TEG applications [17,18], introducing a dynamic 2-dimensional spatially distributed approach for modelling the heating and cooling flows at the TEG facets, the thermoelectric and the heat transport phenomena. Compared to other literature works, our model is modular and supports the evaluation and verification of a plethora of novel concepts for marine energy recovery systems with TEG elements. The model structure follows the physical system characteristics, including connectors for mass, heat and energy flows. Due to its modularity and flexible connectivity, the model can be integrated into complex process flowsheets that include components with mixed