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Exploring the potential for waste heat recovery during metal casting with thermoelectric generators: On-site experiments and mathematical modeling

Marit Takla Børset [a], Øivind Wilhelmsen [b, c], Signe Kjelstrup [a], Odne Stokke Burheim [c, *]

[a] Department of Chemistry, Norwegian University of Science and Technology, NO-7491 Trondheim, Norway
[b] SINTEF Energy Research, N-7465 Trondheim, Norway
[c] Dep. Electr. Engin. Renewable Energy, Faculty of Technology, NTNU, Trondheim, Norway

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ABSTRACT

Thermoelectric power generators are scalable and simple systems for recovering waste-heat disposed by the industry. We combine on-site measurements and a mathematical model to study the potential for power generation with this technology from heat available from casting of silicon. We implement a 0.25 m^2 thermoelectric generator (TEG), based on bismuth-tellurium modules, in the casting area of a silicon plant. The measured peak power is 160 W m^{-2} and the corresponding maximum temperature difference across the modules is 100 K. We predict a large potential to increase the power generated beyond the measured values. For a two-fold increase of the heat transfer coefficient at the cold side, and by moving the generator closer to the heat source, we predict that the power output can reach 900 W m^{-2}. By tailoring the design of the TEG to the conditions encountered in the industrial facility, it is possible to generate more power with less thermoelectric material. We provide guidelines on how to design thermoelectric systems to maximize the power generation from waste heat given off from silicon during casting.

1. Introduction

Access to energy in the right form, at the right time, and at the right place is a premise for our society to continue to prosper. Accordingly, with the stipulated population growth and increase in welfare, the power production must continue to grow, however in appropriate ways [1]. The power supply for a modern society must deal with production, storage and distribution and must come from diverse sources. Moreover, for the society to be sustainable the sources of energy supply must eventually be renewable. Reusing a waste, such as waste heat, is considered a conditional renewable energy source. Furthermore, meeting the future need of power supply requires that we also deal with the concept of energy quality. Electric energy is for instance of greater value than thermal energy. Heat at high temperatures is of greater value than at lower temperatures. Heat on demand is of greater value than intermittent and distributed heat. Thermoelectric generators represent a scalable and robust technology to convert waste-heat to high quality electricity. In this paper, we investigate the implementation of thermoelectric generators in the metal casting industry, where intermittent high quality heat is available alongside with a power demand.

Thermoelectric generators (TEGs) convert a thermal potential (temperature difference) directly to an electric potential (voltage) when heat passes through the generators [2]. To our knowledge, this effect was first discovered in the 19th century by Seebeck [3]. The Seebeck effect occurs when two different charge conductors (*e.g.*, p- and n-type semiconductors) are coupled in series via two connections (A-B-A) and when the connections are at different temperatures (A-B at T_1 and B-A at T_2). As long as the temperatures T_1 and T_2 deviate, we can measure an electric potential in the circuit that is proportional to the temperature difference, where the slope equals the Seebeck coefficient, α, of the pair of conductors. Thermoelectric generators are scalable systems, ranging from micro-watts to kilo-watts applications [4,5]. The efficiency of a TEG relative to the Carnot efficiency is typically below 5%, which is

* Corresponding author.
E-mail addresses: marit.takla@gmail.com (M.T. Børset), oivind.wilhelmsen@sintef.no (Ø. Wilhelmsen), signe.kjelstrup@ntnu.no (S. Kjelstrup), odne.s.burheim@ntnu.no (O.S. Burheim).

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significantly lower than the same relative efficiency of competing technologies such as steam turbine systems and organic Rankine cycle systems, where steam turbine systems can have efficiencies relative to the Carnot efficiency that exceed 40% [6]. The main advantages of TEGs compared to alternative technologies are their size (plates of a few millimeters), scalability, fairly simple constructions (no moving parts), weight (used for mobile applications) and flexibility (fitting to intermittent heat sources) [6].

There are many materials available for use when it comes to thermoelectric generators. Those most commonly referred to are inorganic, and are applicable for temperatures up to 550 K (BiSnTe-based, BiSbTe-based), up to 800 K (PbTeSe, PbSe-based) or up to 1200 K (SiGe) [6]. One obvious goal in the development of thermoelectric generators is to have a large Seebeck coefficient (α) for the materials. This is observed for conducting organic systems [7,8] as well as for membrane and super-capacitor systems [9–11]. Recently, Børset et al. [12] and Kang et al. [13] reported very high Seebeck coefficients (0.9 mV/K < α < 1.3 mV/K) using molten carbonate cells reversible to carbon dioxide and oxygen for the temperature range above 650 K.

However, to develop TEGs requires more than just high Seebeck coefficients [6,14,15]. Cost, energetically and financial, obviously have to be taken into account. On the energetic side, the figure of merit *ZT* is frequently used to characterize the capability of a material to convert heat to electricity [6] and should be as large as possible to obtain a high conversion efficiency. The parameter includes the material's Seebeck coefficient, electrical conductivity and the thermal conductivity (measured at zero electrical current). Fiscal costs are related to raw material costs, purification and assembly of the TEG module in addition to the auxiliary system (cooling and heating system) [14,15]. Regardless of the source, it will always be beneficial for the TEG cost to reduce the module fill-factor (f_{Am}), *i.e.* the fraction of the cross section in a thermoelectric module that is filled with active material, and the conductor thickness [14,15]. There is, however, a complex interplay between thermal and electrical properties, both dependent on cross-sectional areas and thicknesses of the conductors, and the optimum design is a trade-off of these properties [15]. Higher temperature difference is beneficial to power generation, and can be obtained by reducing the cross-sectional areas of the conductors and by increasing the thicknesses. At a given conductor thickness, the thermal conductivity of the thermoelectric module can be reduced by reducing the fill-factor, but lowering the filling degree too much will make the temperature differences across the TEG module increase to an extent that the materials cannot sustain and thus lowering the feet length is required. This means that if correctly optimized, one can have more power with less use of material. This is an attractive possibility we shall further explore in this work.

Regardless of the TEG module end cost, one must always make sure to operate the TEG within the feasible temperature range for material stability. Many materials have been tested and evaluated with respect to performance from a *ZT*-factor, module feet length, and filling degree parametric point of view [14,15], but very few studies look into actual implementation outside the laboratory [15,16]. Several works have studied thermoelectric generators from a purely theoretical perspective [17–25], through a combination of theory and laboratory experiments [26–29] or through laboratory experiments [30–32]. However, to be able to enhance the performance of TEGs for industrial waste heat recovery, it is essential to combine on-site experiments with mathematical modeling.

In this work, we shall take the next step towards industrial applications of TEGs by combining on-site experiments and mathematical modeling to investigate the potential of this technology for power generation from heat available during casting of silicon. Previous work has documented that by recovering the waste heat during silicon casting, it is possible to increase the exergetic efficiency from 0.33 to 0.41, i.e. by 24% [33,34]. In silicon production, silicon is cast in batches where heat is sporadically available. A TEG could thus provide the power needed during the casting process. We develop in this work a mathematical model that has a sufficient level of complexity to capture the main characteristics of the experimental results, but is flexible enough to explore a large range of possible TEG configurations. By taking advantage of the model and the measurements, we show how to enhance the power output of the TEG with less use of material. Moreover, we propose a novel methodology for designing TEG generator systems, opposed to evaluation of single modules which is what is more common in the literature.

The outline of the paper is as follows: In Sec. 2 we give the details of the thermoelectric generator, the casting situation and the testing facilities. The experimental set-up establishes a base case for the model. We then describe the mathematical model, the model parameters applicable to the experimental set-up and give the calculation details in Sec. 3. In Sec. 4 we discuss first the experimental results and compare the model predictions to the measured data to verify that the model captures the experimental results. We then use the model to study how changes in design and location affect the power output and reveal a significant potential to tailor the design of thermoelectric generators to recover more waste heat from silicon casting and simultaneously use less material.

2. Experimental

In this section we give the details of the thermoelectric generator [16], the casting process, testing facilities and testing procedure.

2.1. System description

A thermoelectric generator was constructed consisting of 36 thermoelectric modules based on bismuth tellurium (TEP-1264-1.5, Thermonamic, China). The TEP-1264-1.5 module consisted of 126 pairs of p- and n-type semiconductors connected electrically in series and kept between two ceramic plates (electrically non-conductive material in Fig. 3). Each module was square-shaped of size 40 mm × 40 mm. Thus, for 36 thermoelectric modules the total module surface area was 0.0576 m^2. The modules were arranged in a six by six matrix, connected electrically in series of six ($N_s = 6$), and six series were connected in parallel ($N_p = 6$), see Fig. 1.

In addition to the thermoelectric modules, the generator consisted of a heating block and a cooling block; the modules were sandwiched between them. The heating block and the cooling block were made of aluminum because aluminum has high thermal conductivity, good machinability and it is easily accessible. Soft graphite sheets with a very high thermal conductivity were used as thermal interface material between the thermoelectric modules and the aluminum plates to ensure a low thermal resistance. The heating block was made of 36 square-shaped units (10 mm thick), one for each thermoelectric module. Each unit's surface was 80 mm × 80 mm on the side facing the heat source, while the surface was 49 mm × 49 mm for the side in contact with the thermoelectric module. The purpose of this design (see Fig. 2a) was to concentrate the heat flux into the thermoelectric modules. The cooling block was made of a 25 mm thick aluminum plate (0.5 m × 0.5 m) where water was circulating in a copper pipe (10 mm in diameter and 3.2 m long). The copper pipe was fixed in a channel which was machined into the aluminum plate. We used tap water for cooling (6.0 ± 0.5) °C and measured the inlet and the