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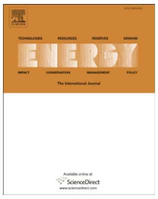

Thermoelectric heat recovery from glass melt processes

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ABSTRACT

Thermoelectric energy recovery from waste heat in glass melting process is investigated without any detrimental design or process changes. Melting glass pellets require a furnace with temperature over 1500 °C for downstream glass shaping processes and hence a large amount of exergy is available but currently destroyed. Due to high temperature gradients, parasitic losses are investigated in conjunction with the optimum thermoelectric design for maximum power output and the lowest cost. Among variations of thermal paths, the fireports are identified as the best potential for lowest cost. By partially replacing the refractory wall in thickness with a thermoelectric generator, heat loss is kept at the current 9 kW/m^2. High temperature gradients across the thermoelectric generator requires a water cooling heat sink. The cost of the heat sink is included in the overall energy and cost analysis. Based on a typical thermoelectric figure-of-merit ($ZT = 1$), optimally designed thermoelectric integrated system generates 55.6 kW of electricity with efficiency of over 15% from a 500 ton/day (5.8 kg/s) scale glass production at an additional cost of $ 1–2/W. This technology can provide 1.37 billion kWh of primary energy savings annually, if it is implemented throughout the whole glass industry in U.S.

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1. Introduction

According to the Lawrence Livermore National Laboratory, the energy flow chart of the U.S.A. for the year 2015 [1] shows that 24.5 Quads (7.18×10^{12} kWh) of energy was used for industrial processes. About 86.7% of the overall industrial energy consumption comes from fossil fuels such as natural gas and coal. The U.S. glass industry produced approximately 20 million tons of glass by consuming 3.3×10^{14} BTU (9.70×10^{10} kWh) of primary energy annually in 2004 [2]. Even though this is a fraction of the whole industrial energy consumption, the fuel energy cost was reported to be $1.6 billion which is 14% of the overall cost of glass products. These high intensity chemical energies, categorized as “in services,” were used for processes including melting target substances in a high temperature furnace. However, due to a large mismatch between the furnace temperature and the melting point of the production raw materials, a significant amount of exergy is typically destroyed. A significant fraction of high temperature heat is irreversibly lost through furnace chamber structures and other refractory walls to the ambient.

This work focuses on waste heat from a glass melting process and the energy recovery with a thermoelectric power generator (TEG). Experimental studies on waste heat recovery have been reported recently, e.g. capturing thermal energy from a steel melting process such as Ebling [3] and Kuroki [4] in experimental study. In Ref.3, despite of successful energy harvesting, the power output was much lower than expected from high temperature heat source. It could be due to the use of commercially available bismuth-telluride for the thermoelectric material, which does not match the application temperature, and the non-optimum co-design of thermoelectric modules with the heat exchanger. Present analytic study includes a similar case as in the literature, and further investigates several approaches to obtain a cost effective waste heat recovery across industrial glass processes. Several technical approaches can be considered during the glass melt process; Regeneration of heat for preheating air with a recuperator [5], thermodynamic heat recovery from exhaust, or preheating of exhaust gas for toxicity treatment [6]. Another approach is design of the furnace for better efficiency with simulation [7]. A Rankine cycle waste heat recovery may also be an option. Organic Rankine cycle has been well studied, but operational temperature is limited to 300 °C range [8], so this is not applicable.

In a previous study, a topping cycle TEG was investigated with

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conventional superheated steam Rankine cycles [9] since the steam temperature is limited to 540 °C - 640 °C, primarily associated with the reliability of turbine blades [10]. The study reported a potential 6% overall efficiency improvement for a power plant using available high temperature thermoelectric material with a figure-of-merit (ZT ~ 1). Given that the heat source temperature is 1500 °C, the thermoelectric material must cover a temperature range 700–1000 °C at the optimum design, given that temperature drop across TE elements should be approximately half of the total temperature drop between the heat source and the heat sink [11]. A well-known, high-temperature material is silicon-germanium (SiGe) utilized for space crafts for more than forty years. The material performance has been enhanced using e.g. nanostructured SiGe [12]. The Jet Propulsion Laboratory (JPL) has recently developed segmented unicouples for integration into an advanced radioisotope thermoelectric generator (RTG) [13]. The high-temperature segments are composed of p-type $Yb_{14}MnSb_{11}$ and n-type $La_{3-x}Te_4$ sustaining at temperatures up to 1000 °C and the lower segments are made of skutterudite (SKD) materials that are capable of long-term operation up to 600 °C. In this study, we estimate the approximate cost and efficiency of waste heat recovery in different locations in glass melt processing using already demonstrated thermoelectric materials. We assume average thermal conductivity, electrical conductivity, and Seebeck coefficient that will give ZT ~1 at the mean operation temperature. This analysis can be extended in the future by taking into account the specific temperature-dependent material properties.

Adding a TEG in the furnace or boiler segment could be done in conjunction with a change in the glass process flow [14]. This study, however, focuses on the TEG replacing a fraction of the refractory wall thickness, keeping the wall total thermal resistance unchanged. Hence no modification is required in the current glass process. The TEG design is then optimized for maximum power output and the low cost. Due to high temperature gradients, key heat loss mechanisms are taken into account. The benefits of a TEG are highlighted in a comparison with other waste heat recovery energy conversion technologies.

2. Glass melt process and TEG integration

Fig. 1 shows the cross sectional sketch of a glass melt process. Four locations are identified for waste heat energy harvesting with TEGs: (a) crown ceiling of the glass melt pool, (c) sidewalls of the glass melt pool, (c) fireports, and (d) the melt glass cooling in a preforming process. The bottom wall of the pool is excluded since the integration could be overly challenging. Melted glass from the pellets must maintain a temperature of 1400–1500 °C in the pool, while the furnace hot gas temperature exceeds that temperature [15]. Although the pool is built with thick refractory walls [16], heat loss per unit area is in the range of 9 kW/m^2 at fireports and around 3 kW/m^2 at other walls [17]. The heat demand is 12.5 MW for melting glass pellets in 500 ton/day (5.8 kg/s) production. This is based on 2172 kJ/kg of tangible heat for melting pellets at 1500 °C [18]. Table 1 summarizes the available waste heat at different locations. These heat fluxes are the maximum allowable heat flux (q_{limit}) for the design of waste heat recovery while maintaining the fuel burning rate constant. Fig. 2 shows the overall energy flow of a glass melt process and the amount of waste heat at various locations.

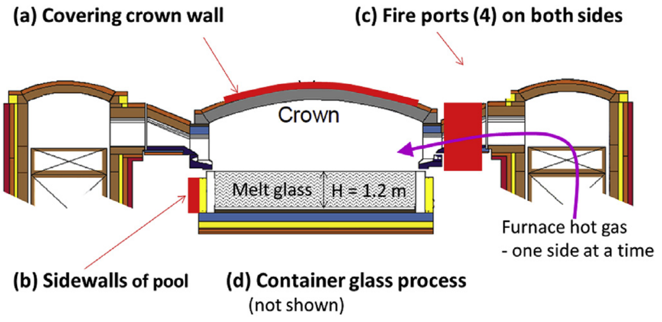

Fig. 1. Cross sectional sketch of glass meting pool indicating locations of potential waste heat recovery.

Using the model described later in the manuscript, the approximate amount of electric energy possible from the waste heat and the associated system costs are estimated and summarized in Table 2. Sketches showing potential integration of a TEG at the locations of interest are shown in Fig. 3.

According to the above study, the four fireports are the best location for high temperature waste heat recovery with lowest cost. Partial replacement of the refractory walls impacts both the available energy and the cost. In the following detailed analysis, a high temperature TEG is optimized taking into account parasitic heat losses.

3. Modeling of TEG for high temperatures

Waste heat recovery from a glass melt process does not require additional fuel; the goal is to convert part of the heat leakage into useful work. Here a model is developed to maximize the power output according to Curzon and Ahlborn [19] rather than pursuing the highest efficiency.

3.1. Maximum power output design of TEGs

The optimization follows a generic model according to Yazawa et al. [11] considering a constant figure-of-merit (ZT = 1) for both the p-type and n-type materials. The temperature reservoirs, T_s for heat source and T_a for ambient are given. A thermoelectric module consists of n elements in an area A [m^2]. For simplicity, temperature-independent material properties are assumed for the n-type and p-type elements. Without any parasitic losses involved, the ideal power output per unit area w [W/m^2] is formulated as follows, knowing the hot and cold temperatures T_h and T_c of thermoelectric element, respectively:

$$w = I^2 R_L \big/ A \tag{1}$$

$$R_L = mR = m\frac{nd_{TE}}{\sigma F(A/n)} = m\frac{n^2 d_{TE}}{\sigma FA} \tag{2}$$

$$I = \frac{nS(T_h - T_c)}{(1+m)R} = \frac{S(T_h - T_c)}{(1+m)}\frac{\sigma FA}{nd_{TE}} \tag{3}$$

Substituting Eqn. (2) and Eqn. (3) into Eqn. (1), and using the relation $S^2\sigma = \beta Z$ by definition of the figure-of-merit Z, one obtains:

$$w = \frac{m\sigma S^2 F}{(1+m)^2 d_{TE}}(T_h - T_c)^2 = \frac{mZ}{(1+m)^2}\frac{\beta F}{d_{TE}}(T_h - T_c)^2 \tag{4}$$

where, R_L is load resistance, R is internal electrical resistance of TE legs, and m is defined as $m = R_L/R$. The electrical-thermal optimum design is found when $m = \sqrt{1 + Z\overline{T}}$ at mean temperature $\overline{T} = (T_h + T_c)/2$. I is electrical current in the circuit, F is fractional area coverage of a thermoelectric element, d_{TE} is the thickness (element length), and β is the thermal conductivity of thermoelectric material. Eqn. (4) can be directly derived similar to the

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