

Industrial Solid-State Energy Harvesting: Mechanisms and Examples

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ABSTRACT

This paper explores the potential for solid-state energy harvesting in industrial applications. In contrast to traditional heat recovery, the output of solid-state devices is electricity, which can be readily used in virtually any plant. The progress in harvesting waste heat via thermoelectric and thermionic generators is described. With second law efficiencies now approaching 50% and 80% respectively, we show that these technologies are on the cusp of practical use. Finally, we present an example of energy harvesting using thermionic devices in an industrial application. The example considers energy harvesting from a furnace at a glass manufacturing facility where exhaust gases are discharged at about 2,400°F and where there are no viable uses for recoverable heat. An optimal configuration of thermionic devices is shown to be capable of recovering nearly 1/3 of the available exergy in the exhaust gases as electrical energy.

Introduction

Diminishing fossil fuel resources and increasing global demand are increasing the cost of fossil fuels. In addition, anthropogenic global warming is motivating many companies, regions and countries to reduce CO₂ emissions. It is therefore increasingly important to maximize the utilization of fossil fuel resources. Many thermally intensive processes exhaust high-quality energy to the environment. Frequently, heat exchangers are used to recover some of the exhausted energy, but at a diminished quality. The diminished quality of recovered energy limits its application and increases the cost of equipment needed to transport and apply the energy. This paper explores the potential for solid-state energy harvesting in industrial applications. In contrast to traditional heat recovery, the output of solid-state devices is electricity, which can be readily used in virtually any plant.

In some respects, engineers have always been engaged in “energy harvesting”. Early technologies harvested energy from streams and wind for manufacturing and transportation. In the early 1700’s, Thomas Newcomen forever changed the world by inventing the first practical machine to convert thermal energy into useful work. Over time engineers have continually improved the efficiency of these energy conversion devices, in part by finding a use for the energy that otherwise would be wasted. Today, this theme of finding a use for what otherwise would be wasted is prominent in Lean Manufacturing, which seeks to minimize waste. It is also prominent in TRIZ, the increasingly popular Russian strategy for inventive problem solving where one of the forty universal design principles is to “retain the available,” e.g., to find uses for what normally is wasted (Altshuller and Shulyak 1998).

In thermal industrial processes, the “use the waste” concept has been manifested in a variety of ways. The most common way is to transfer heat from higher quality waste streams to lower quality supply streams. The economic success of these applications depends in large part on the availability of low quality supply streams and the proximity of these streams to the high quality waste streams.

Recently the “energy harvesting” nomenclature has emerged in the aerospace field. Driven by the goal of developing such things as self-powered sensors, distributed actuation systems, and surveillance devices, DARPA has invested in solid-state energy harvesting systems; namely thermoelectric, thermionic, and piezoelectric devices. This interest has rendered substantial improvements in both the 1st and 2nd thermodynamic law efficiencies of the solid-state energy harvesting devices. In addition, this research has increased interest with respect to their practical utility. For example, Hallinan et al. (2005) demonstrated that thermal energy harvesting from aircraft radar elements has immediate benefits, even with the current thermoelectric technologies.

Others have demonstrated the promise of energy harvesting in automotive applications. For example, Bell (2004) showed that solid-state thermal energy recovery devices could find significant applications in the automotive industry if mass produced. In addition, Fairbanks noted (2004) that continued improvements in solid-state thermal energy harvesting at the rate realized over the past six years could make solid-state power conversion competitive with the internal combustion engine. Finally, Elder et al. (2004) found that solid-state thermal energy harvesting for automotive applications is possible if the module cost can be brought down to approximately 0.10 \$/W over a large temperature range. With mass production, such costs may be feasible.

Taking advantage of the intense push in the defense arena to further develop solid-state energy harvesting devices, it is now timely to consider the possibility of employing solid-state energy harvesting systems for industrial waste-energy conversion. The United States Department of Energy Industrial Technologies Program has established an initiative aimed at integrating high *ZT* thermoelectric materials in the more energy intensive materials processing arena (DOE 2004). The first International Energy Harvesting Conference was hosted in 2004 in the United States. The 2006 ASME Mechanical Engineering Congress and Exhibition is hosting four sessions on energy harvesting.

As described by Ayres, the American Physical Study sponsored a study in 1974 which concluded that the industrialized economy then had a 2nd law efficiency of 2.5-3.0%. This estimate was later revised to 3-3.5% (Ayres et al. 1998). One can conclude that there is ample opportunity in industry to recover exergy across all segments of industry and society at large.

This paper addresses three aspects of industrial solid-state energy harvesting. First, it provides a description of the evolution and state-of-the-art for the most prominent solid-state energy harvesting devices; namely thermoelectric and thermionic generators. Second, given this state of the art, the overall implications of employing energy harvesting on a massive scale in U.S. industries is examined. Third, a specific example of employing thermionic energy harvesting devices in a glass manufacturing application is considered.

Solid-State Thermal Energy Harvesting

Thermoelectric generators and thermionic devices are two prominent solid-state energy harvesting strategies which possibly have future merit for industrial applications. Both types of devices convert waste heat to electrical energy. Both technologies are briefly discussed.

Thermoelectric Generators

Thermoelectric (TE) generators are solid-state semi-conductor-based heat engines which transport thermal energy to electrical power. As heat flows from the hot side of the TE device to the cold side, a portion of that heat is converted into electricity. TE device operation is based upon the Seebeck effect – discovered by physicist Thomas Seebeck in 1821. The Seebeck effect indicates that a voltage difference is induced across a material when a temperature difference is applied across the material. While this effect has been known for almost 200 years, thermoelectric devices have only been considered for power generation during the past 50 years.

The limiting thermal efficiency in converting heat to electricity is the Carnot efficiency (Equation 1).

$$\eta_{Carnot} = 1 - \frac{T_C}{T_H} \quad (1)$$

where T_C and T_H are the cold- and hot-side temperatures of the devices, respectively. The Carnot thermal efficiency represents the maximum efficiency possible. Historically, the performance of TE devices has fallen far short of this maximum efficiency.

The relative performance is primarily dependent upon the dimensionless thermoelectric figure of merit, ZT (Equation 2).

$$ZT = \frac{\sigma S^2}{\beta} T \quad (2)$$

Where, σ and β is the electrical conductivity and thermal conductivity of the material, respectively, and S represents the Seebeck coefficient. The higher the Seebeck coefficient, the stronger the thermoelectric effect of the material. For steady-state conditions, the TE generator efficiency can be related to this figure of merit and the device's hot- and cold-side temperatures, T_H and T_C (Equation 3).

$$\eta_{TE} = \frac{T_H - T_C}{T_H} \left(\frac{\sqrt{1 + ZT} - 1}{\sqrt{1 + ZT} + T_C/T_H} \right) \quad (3)$$

Equation 3 shows that a material with a higher ZT value used for TE generation leads to higher operational efficiencies. Thus, a good material for thermoelectric applications is one that features high electrical conductivity, low thermal conductivity, and a high Seebeck coefficient.

Thermionic Generators

Like thermoelectric devices, thermionic generators convert a portion of waste heat into electrical energy. This conversion is also a result of a temperature difference between the heat source and sink. However, unlike thermoelectric devices, the mechanism for the energy conversion is thermionic emission rather than the Seebeck effect. Thermionic emission is a

phenomena where electrons flow through a vacuum from a metal to a metal oxide surface as a result of a temperature difference. For thermionic emission, the higher the temperature difference the greater the thermionic emission. However, similar to TE generators, thermionic generators are limited by the Carnot efficiency. Kilgrew (2002) outlines the development of Power Chips technology, a new type of thermionic device that allows power to be generated by a process known as “thermo tunneling”. This technology claims to achieve thermal to electrical conversion efficiency near 60%-70% of Carnot efficiency. Other work has shown similar increases in efficiencies. Humphrey et al. (2005) demonstrate potential thermionic generator efficiency improvements of about 25%. Zheng (2006) shows that the efficiency can be 50% of the Carnot efficiency using thermionic-tunneling multilayer nanostructures. Mahan (1994) predicted efficiencies as high as 80% of the Carnot efficiency using high performance multi-barrier thermionic devices.

Until recently, thermionic generators were only feasible for power generation at very high temperatures ($T_H > 1000$ K). However, advances in thermionic device technology hold incredible promise. Substantial research oriented toward the development of thermionic devices capable of efficient operation at lower temperatures is being conducted (Shakouri and Bowers 1997a, Shakouri and Bowers 1997b, Mahan and Woods 1998, Mahan et al. 1998, Shakouri et al. 1999, LaBounty et al. 2000, Fan et al. 2001a, Fan et al. 2001b, Hishinuma et al. 2001, and Hishinuma et al. 2002). These thermionic devices hold incredible promise for future use.

Combined Thermionic and Thermoelectric Systems

As illustrated in the previous sections, thermionic devices are often more efficient than thermoelectric devices at very high temperatures, while thermoelectric devices often perform better than thermionic devices at low temperatures. These complimentary characteristics make it possible to use thermionic and thermoelectric devices in tandem to achieve greater efficiency. For example, a thermionic device could use a high temperature source to generate power and a thermoelectric source could then harvest additional energy from the waste heat of the thermionic device. Such a tandem system could be used to improve the overall system performance.

Potential for Solid-State Energy Generation in Industry

The power generation potential from using thermionic or thermoelectric devices in the industrial sector is large. Many industries have thermally intensive processes which exhaust medium-to-high temperature, high-quality energy as waste heat to the environment. Moreover, many of these same industries also use low temperature sinks in their processes. Because electricity can be readily used by virtually any industrial facility, the industrial sector is a perfect candidate for the use of either or both thermionic and thermoelectric devices.

Yodovard et al. (2001) examined the impacts of implementing thermoelectric energy recovery systems throughout the industrial sectors of Thailand. This study primarily addressed the economic feasibility of waste heat recovery and thermoelectric generation from the stacks of diesel cycle and gas turbine cogeneration plants. From an estimated 2,160 MW (thermal) of total waste heat, about 100 MW of electricity could be generated.

Kyono et al. (2003) analyzed the potential for electricity generation from heat loss in the condenser of a pre-existing 700 MW steam-based power plant; where steam-based power plants

lose about 60% of input energy as waste heat. Estimates indicate about 126-164 kW of total electricity could be generated from the power plant's waste heat.

In addition, Margulies et al. (1985) developed a conceptual design for a thermionic cogeneration system in which multiple thermionic generators were applied to the external surface of industrial boilers in a chlorine caustic soda production plant. Similarly, the United States Department of Energy provided a scoping study of the potential for thermoelectric generation in three large-scale, high-temperature-discharge industrial processes: glass furnaces, aluminum Hall-Hèroult cells, and reverberatory furnaces (DOE 2006). These processes were found to be favorable applications of thermoelectric devices due to the high amount of high quality waste energy and need for electricity generation onsite.

Case Study: Energy Harvesting from Glass Melt Oven Stack

This case study investigates the potential for thermionic generation from a glass melt oven. An energy assessment was conducted for a large fiberglass factory in northwest Ohio where a large glass melt oven was exhausting large quantities of high-temperature (~2400°F), high-quality waste heat. In addition, the facility requires a significant amount of electricity for operation. Thus, the assessment yielded the potential for implementation of thermoelectric generation. This case study presents the past and current state of operation, the theoretical design of a possible thermoelectric system, the analytical model used, and the theoretical results if thermoelectric generation were to be implemented. The goal of the analysis is to ascertain the potential for energy harvesting via state-of-the-art thermionic devices.

Past and Current Operation

At one time, the glass melt oven employed an annular heat exchanger to reclaim thermal energy from exhaust gases (Figure 1a). A schematic and the geometric properties of the annular heat exchanger are shown in Figure 1b and Table 1, respectively. Reclaimed thermal energy was used to pre-heat the oven's combustion air. According to facilities personnel, the mass flow rate of exhaust from the oven is about 32,670 lbm/hr and the heat exchanger was able to transfer about 8.428 MBtu/hour to pre-heat inlet combustion air to about 1250 °F when operational. In an effort to improve emissions and increase the oven's efficiency, combustion air was replaced with near-pure oxygen. By replacing combustion air with oxygen rendered the annular heat exchanger useless. Thus, no thermal energy is reclaimed from the exhaust stack.

Design of Possible Thermionic System

A conceptual design for use of thermionic devices and electricity generation is posed in Figure 2. Thermionic devices are chosen because of the exposure to a high hot-side temperature (exhaust side). Thermionic devices are sandwiched between the exterior surface of the exhaust stack and interior surface of the outer annulus. Thus, heat transferred from the exhaust gases passes directly into the thermionic devices. In an effort to both realize a greater temperature difference across the thermionic device (to increase efficiency) and increase the heat transfer into and through the thermionic device, air is pumped through the outer annulus. This reduces

convective thermal resistance on the exterior of the thermionic and reduces the cold side temperature of the thermionic devices.

Figure 1. (a) Glass Melt Oven with Annular Heat Exchanger and (b) Schematic of Annular Heat Exchanger

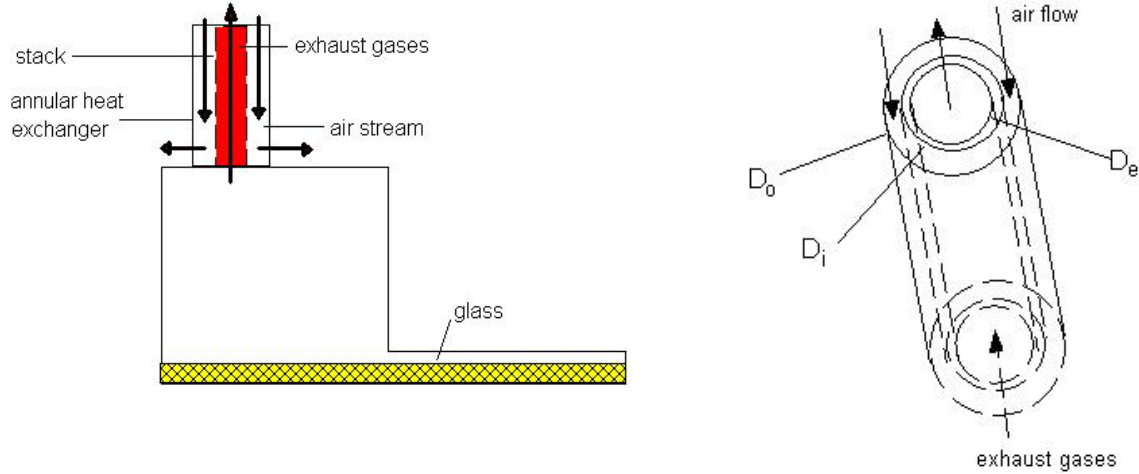
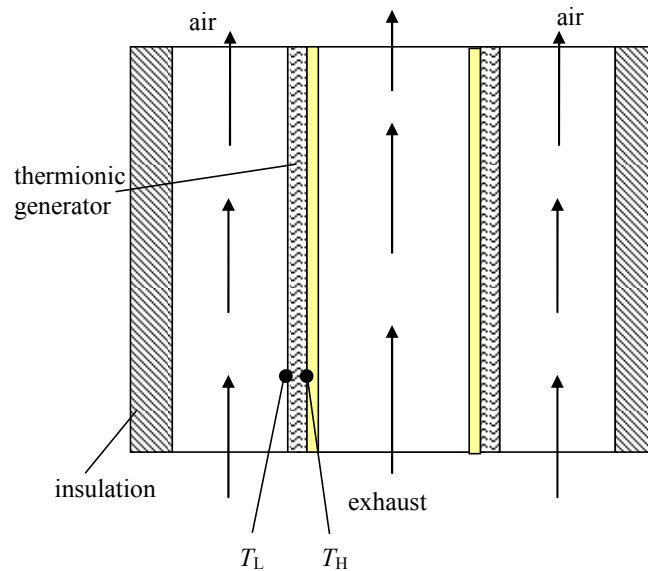


Table 1. Baseline Geometrical Properties of Stack/Heat Exchanger System

Variable	Description	Value
D_e [feet]	Exhaust Stack Outer Annulus Diameter	10
D_i [feet]	Exhaust Stack Inner Annulus Diameter	5
t [inches]	Exhaust Stack Wall Thickness	0.125
L_{stack} [feet]	Length of stack	20

Figure 2. Schematic of Stack/Energy Harvesting System



Modeling Thermionic Generation

The model posed aims at providing a rough assessment of the potential for energy harvesting in this glass melt furnace application. General assumptions employed in the model include the following:

- The internal wall temperature in the stack is assumed to be equal to the temperature of the exhaust gases at any axial position within the stack. This assumption accounts for the fact that gas radiation dominates the heat transport from the exhaust gases to the wall.
- The conductive resistance through the wall of the stack is negligible relative to other thermal resistances considered.
- Steady-state conditions exist.
- The external wall of the annular heat exchanger is assumed insulated, and thus this exterior wall is a re-radiating surface. The net thermal radiation from the interior wall to the exterior wall of the annular heat exchanger is therefore negligible.
- For now, the exergy transferred into the air stream pumped through the annular heat exchanger is not utilized, as presently there are no identified opportunities for heated air in the plant.

Relative to the thermionic devices, the following assumptions are utilized. First, the thermionic devices are assumed to blanket the exterior surface of the exhaust stack. The cold-side surface of the thermionic devices represents the interior surface of the outer annulus of the heat exchanger. In practice, this assumption is not likely, as the devices would ideally be placed strategically in a periodic arrangement to rely upon their greater power density. Second, the thermionic devices selected have an evacuated gap.

Energy Balance on Exhaust Stack

An energy balance is performed on the exhaust stack shown schematically in Figure 1b and Figure 2. The energy balance is shown symbolically in Equation 4.

$$\dot{Q}_H'' = \dot{W}_e'' + \dot{Q}_L'' \quad (4)$$

where,

$$\dot{Q}_L'' = \varepsilon\sigma(T_H^4 - T_L^4) = h_a(T_L - T_a) \quad (5)$$

In Equation 4, σ is the Stefan-Boltzmann constant, T_H is the hot-side temperature, T_L is the cold-side temperature, and h_a is the external heat transfer coefficient determined from the Dittus-Boelter relation (Equation 6).

$$h_{air} = \frac{0.023k_{air}}{D_o - D_i} \left(\frac{4\dot{m}_{air}}{\pi(D_o - D_i)\mu_{air}} \right)^{0.8} \left(\frac{\mu_{air}\bar{c}_{p,air}}{k_{air}} \right)^{0.4} \quad (6)$$

Each term of Equation 6 and the specified conditions are provided in Table 1 and Table 4.

Table 4. Air and Exhaust Conditions Considered in the Model

Variable	Description	Value
$\dot{m}_{exhaust}$	Exhaust Stack Mass Flow Rate	4.11 kg/s (32670lbm/hr)
\dot{m}_{air}	Air Mass Flow Rate	<i>Varied</i>
$C_{p,e}$	Average Specific Heat of Exhaust	1.1 KJ/kg K
$T_{e,inlet}$	Exhaust Gases Inlet Temperature	1315 C (2400F)
$T_{air,inlet}$	Air Temperature Inlet Temperature	25 C
$\bar{c}_{p,air}$	Average Air Specific Heat	1.0 kJ/K
μ_{air}	Average Air Kinematic Viscosity	1.8e-5 kg/m s
k_{air}	Average Air Thermal Conductivity	1.38 W/m K
ϵ	Internal Emissivity of Thermionic Device	0.1

In addition, the model considers an energy balance on both the exhaust (Equation 7) and annular heat exchanger air streams (Equation 8). These represent the hot- and cold-side thermionic heat fluxes, respectively.

$$\dot{m}_{exhaust} \bar{c}_{p,e} \frac{dT_H}{dx} = -\dot{Q}_H'' 2\pi D_e \quad (7)$$

$$\dot{m}_{air} \bar{c}_{p,a} \frac{dT_L}{dx} = \dot{Q}_L'' 2\pi D_i \approx \dot{Q}_L'' 2\pi D_e \quad (8)$$

A 2nd law efficiency relates the hot- and cold-side thermionic heat fluxes (Equation 9). A 2nd law efficiency of 0.65 is assumed for the thermionic devices. This is consistent with present state-of-the art of such thermionic devices.

$$\eta_H = 0.65 = \frac{\dot{Q}_L'' / \dot{Q}_H''}{1 - T_L / T_H} \quad (9)$$

The geometric (Table 1) and flow conditions (Table 4) employed are considered constant for all cases and measured by the facility. However, the mass flow rate of air in the outer annulus is varied over a range of 1-6 kg/s. A fourth-order Runge-Kutte solution solver is used to solve the system of equations given by equations (4)-(9).

Results

From the previously specified conditions, model results are discussed. The axial variation of heat flux for a mass flow rate of air of about 3 kg/s is shown in Figure 3a. It is important to note that the energy harvesting flux is certainly greatest at the inlet to the stack where the temperature difference between the exhaust and air is at a maximum. In addition, it is also important to note that the maximum heat flux into the thermionic device is less than 3.5 W/cm², well below the permissible heat flux into a vacuum gap thermionic device. Similarly, Figure 3b shows the axial variation of temperature for the hot- and cold-side of the thermionic device and the air, also for an air mass flow rate of 3.0 kg/s. Lastly, Figure 4 shows the exit hot-

side, cold-side, and air temperature. Analysis of this Figure 4 indicates further possibility to use the heated air within the facility or by a surrounding industry for process heating purposes. This would further increase the amount of heat recovered. Moreover, it is clear from the figure that the exhaust temperature is still very high.

Figure 3. (a) Axial Variation of Heat Flux on the Hot and Cold Sides of the Thermionic Devices ($\dot{m}_{air} = 3.0$ kg/s) and (b) Axial Temperature Variation ($\dot{m}_{air} = 3.0$ kg/s) for Hot-Side, Cold-Side and Air

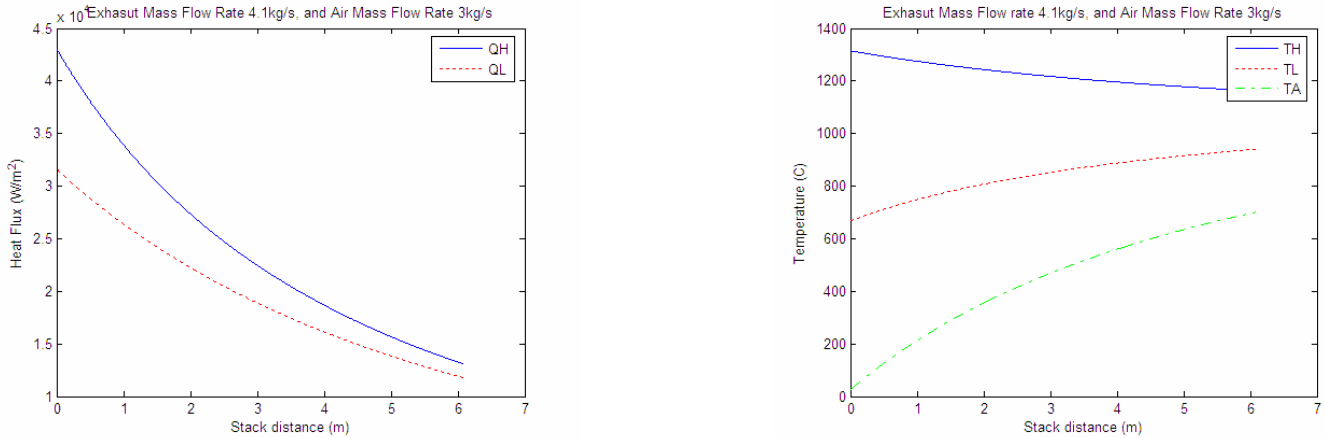


Figure 4. Exit Exhaust and Air Temperature as a Function of the Air Mass Flow Rate

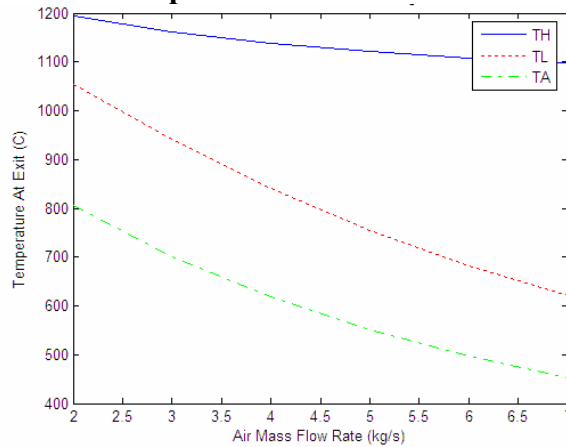


Figure 5 shows the power generated – as a function of the mass flow rate of air – by the thermionic devices under the previously specified conditions.

Exergy (or availability) represents the work potential of any form of energy. For the exhaust and air streams, the availability harvested is found in Equation 10.

$$\dot{A} = \dot{m}[(h - h_0) - T_0(s - s_0)] \quad (10)$$

Figure 5. Power Generated by the Thermionic Devices as a Function of the Mass Flow Rate of Air (20-ft stack)

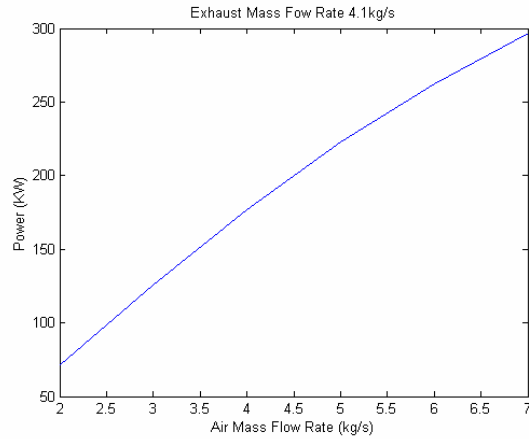
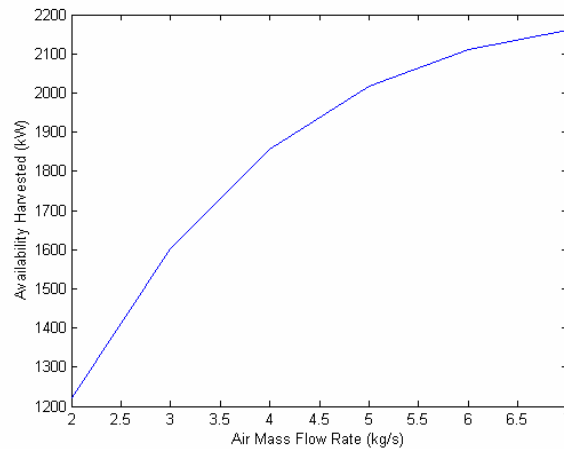


Figure 6 emphasizes the point that there is still work potential in the air stream for the 20-ft (~6 meters) stack case. This figure shows the sum of the availability harvested (electrical energy) by the thermionic devices plus the availability harvested by the air as a function of air mass flow rate. Because of the high exhaust temperatures and the high availability, a longer stack certainly could be considered to increase the amount of heat recovered from the exhaust stream.

Figure 6. Availability Harvested as a Function of the Mass Flow Rate of Air



The case of a longer exhaust stack is considered. The height of the stack is increased to 50-ft (~17 meters). Figure 7 shows the power generated by thermionic devices as a function of the mass flow rate of air, with a 50-ft stack. It is clear that the energy harvested is much greater.

Figure 8a and 8b show the axial temperature distribution for both the exhaust gases and the air and the availability harvested for this 50-ft exhaust stack. These figures indicate that the exhaust gas temperature is substantially decreased for the longer stack. In addition, the amount of availability harvested is dramatically increased. However, it is also clear that as the axial distance increases the amount of energy harvested decreases.

Figure 7. Power Generated by the Thermionic Devices as a Function of the Mass Flow Rate of Air (50-ft stack)

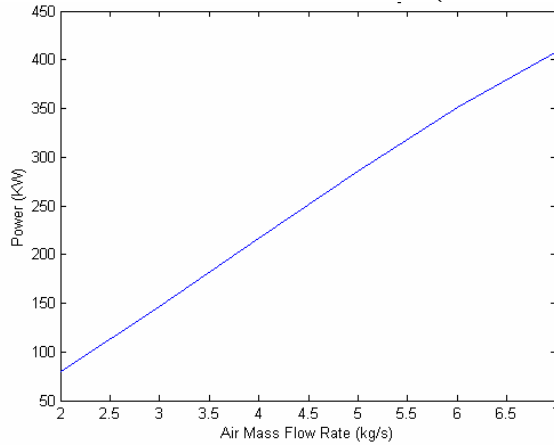
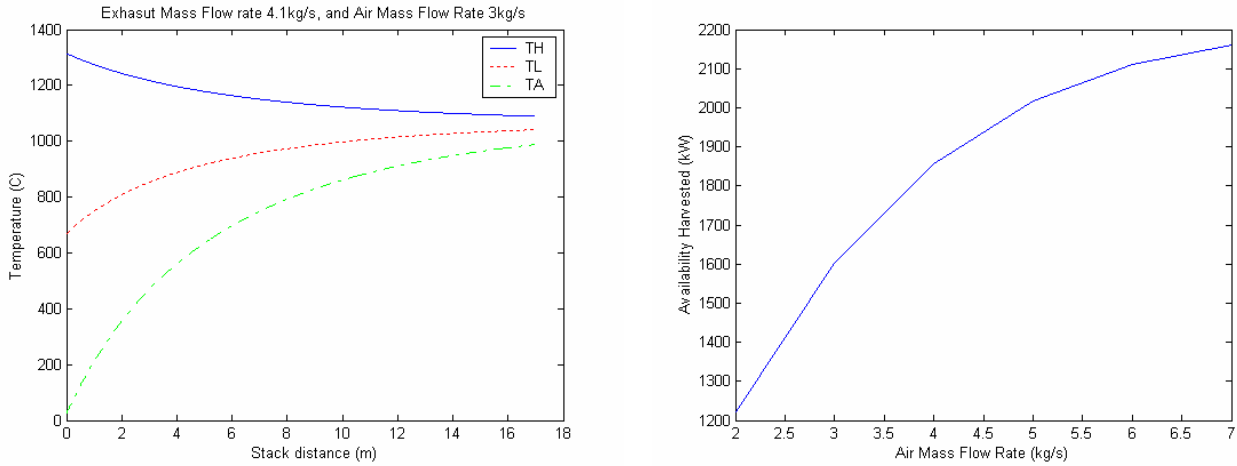


Figure 8. (a) and (b)



Indeed the thermionic devices reclaim energy (exergy), resulting in substantial energy savings per year. The analysis which follows evaluates these savings in the present and in the future and, as well, estimates the cost barrier associated with the thermionic device(s) which must be achieved in order to make thermionic energy recovery in industry economically feasible.

Economic Analysis

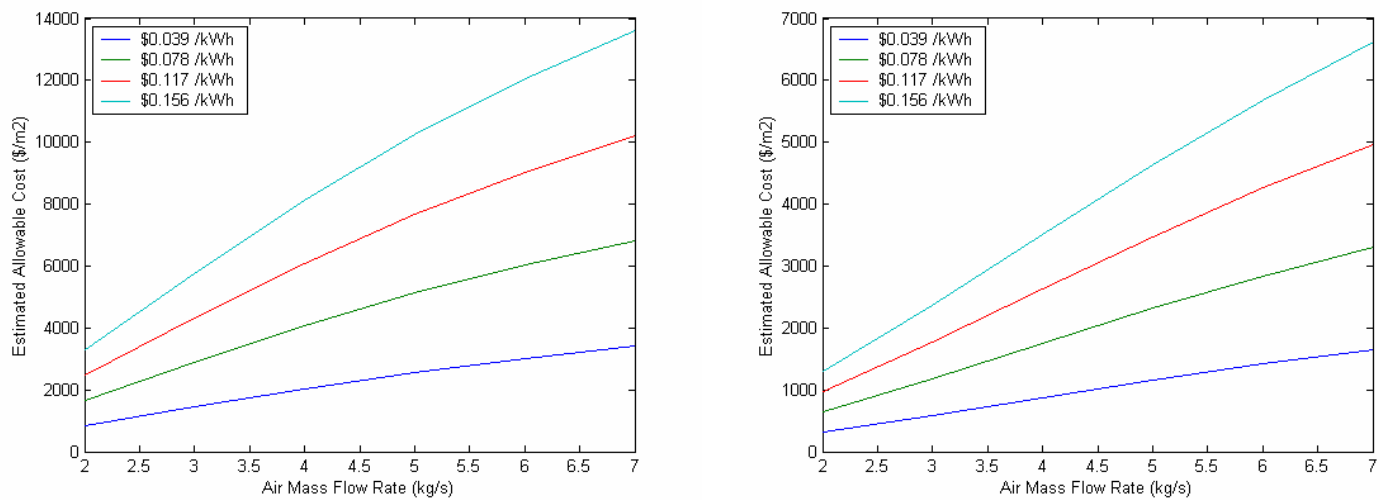
The economic requirements for this application are investigated. Due to the assumption of uniform distribution of the thermionic devices over the surface of the stack, the most favorable economic situation is associated with a shorter stack. This is due to a higher average heat flux for a shorter stack than for a longer.

The allowable initial cost of thermionic devices according to the specified mass flow rate of air is shown in Figure 9. The allowable initial cost is based on a 4 year return on investment if only electrical energy is recovered. A total operating time of 8,760 hours per year is considered. The allowable initial cost considers the current electrical energy cost incurred by the facility (\$0.039/kW-hr) and two potential future cases of electrical energy costing: if the incurred

electrical energy cost were to double (\$0.078 /kW-hr) and if the incurred electrical energy costs were to quadruple (\$0.156 /KW-hr).

The most favorable costing, assuming the cost of auxillary equipment is small in comparison with the cost of thermionic devices, is associated with the maximum mass flow rate of air. For present day electrical energy costs and with the maximum mass flow rate of air, the permissible cost of thermionic devices is about \$1,000 /m². With these conditions, 300W of electrical energy recovery is realizable. The acceptable cost per power is about \$0.55/W (greater than the acceptable cost of \$0.10/W for automotive applications). Alternatively, if the future cost of electrical energy were to be quadrupled from today's cost, the permissible cost of thermionic devices would increase to about \$4,000 /m².

Figure 9. Economic Sensitivity Analysis for Thermionic Devices with (a) 20-ft (~6 meters) Stack and (b) 50-ft (~17 meters) Stack



Conclusions

This paper has provided a review of state-of-the-art thermal energy harvesting technologies feasible for use in industry; thermoelectric and thermionic devices. In addition, this paper has provided a case study of an actual glass melting oven and the potential for implementation of thermionic devices for electrical energy generation. This case study has shown the energy savings potential and the permissible initial costs allowable for acceptance by industry both in the present and the future.

For the future, the real challenge is to work to develop practicable thermal energy harvesting systems. Such systems likely would seek to focus energy normally wasted into the thermoelectric and thermionic devices, which can tolerate very large heat fluxes, such that these devices need not blanket the entirety of heat surfaces. For the long-term it is conceivable that heat pipes/thermosyphons would be used to direct waste energy to periodically spaced energy harvesting devices.

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Acknowledgements

This work was graciously supported by the U.S. Department of Energy Industrial Technologies Program through its support of the Industrial Assessment Center program.