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ANALYTIC OPTIMIZATION OF COST EFFECTIVE THERMOELECTRIC GENERATION ON TOP OF RANKINE CYCLE

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ABSTRACT

Thermoelectric (TE) generators have a potential advantage of the wide applicable temperature range by a proper selection of materials. In contrast, a steam turbine (ST) as a Rankine cycle thermodynamic generator is limited up to more or less 630 ^{o}C for the heat source. Unlike typical waste energy recovery systems, we propose a combined system placing a TE generator on top of a ST Rankine cycle generator. This system produces an additional power from the same energy source comparing to a stand-alone steam turbine system. Fuel efficiency is essential both for the economic efficiency and the ecological friendliness, especially for the global warming concern on the carbon dioxide (CO_2) emission.

We report our study of the overall performance of the combined system with primarily focusing on the design parameters of thermoelectric generators. The steam temperature connecting two individual generators gives a trade-off in the system design. Too much lower the temperature reduces the ST performance and too much higher the temperature reduces the temperature difference across the TE generator hence reduces the TE performance. Based on the analytic modeling, the optimum steam temperature to be designed is found near at the maximum power design of TE generator. This optimum point changes depending on the hours-of-operation. It is because the energy conversion efficiency directly connects to the fuel consumption rate. As the result, physical upper-limit temperature of steam for ST appeared to provide the best fuel economy. We also investigated the impact of improving the figure-of-merit (ZT) of TE materials. As like generic TE engines, reduction of thermal conductivity is the most influential parameter for improvement. We also discuss the cost-performance. The combined system provides the payback per power output at the initial and also provides the significantly better energy economy [$/KWh].

Nomenclature

C: ratio to Carnot efficiency [-]
d: thickness [m]
F: fill factor (fractional area ratio) [-]
G: material price [$/kg]
h: hours of operation [hr]
i: electrical current [A]
I: initial material cost [$]
m: electrical resistance ratio [-]
R: electrical resistance [Ω]
S: Seebeck coefficient [V/K]
T: temperature [K]
w: power output per unit area [W/m^2]
x: thickness ratio [-]
Y: energy production cost [$/KWh]

Z: figure of merit of TE material [1/K]

Symbols

β: thermal conductivity [W/mK]
η: efficiency [-]
ρ: density [kg/m^3]
σ: electrical conductivity [1/Ω.m]
ψ: thermal resistance [K/W]

Subscripts

0: optimum for maximum power
a: ambient
c: cold side
f: fuel
g: interface
h: hot side
in: input
s: substrate for TE modules
ST: steam turbine
TE: thermoelectric

INTRODUCTION

The U.S. energy flow chart [1] shows that the energy in service is only ~41.7% of the energy input in year 2011. This study represents one approach for increasing fuel efficiency in power production and lowering the energy cost [$/kWh]. Among power generators, Rankine cycle steam turbines are widely used for power generation. Steam turbines are also one of the most effective mechanical engines [2] due to its relatively simple structure. Because it is using steam, however, the Rankine cycle has a thermo dynamic limitation. The thermodynamic conversion efficiency is limited by the inlet steam temperature. The structural material of turbines, such as stainless steel, has a temperature-dependent yield limit at the extremely high steam pressure. The Carnot efficiency with 900 K steam temperature and 300 K ambient temperature is only 67%. Considering the realistic irreversible thermal contacts, the efficiency at the maximum power output becomes even lower 42% based on Curzon and Ahlborn [3]. With an analytical approach, we will find the best operating point for fuel economy for the thermoelectric topping cycle steam turbine between the maximum efficiency and the efficiency at maximum power output.

COMBINED-SYSTEM CONCEPT

Adding a thermoelectric (TE) power generator into the gap between the adiabatic flame temperature and the steam temperature will make additional power output. We have studied a combined system composed of a TE generator on top of a Rankine cycle. The TE generates an additional amount of power by using the large temperature gap between the source temperature and the steam temperature. Even with a special design dedicated for high temperature operation for turbines [4], the steam temperature is limited to < 650 ^{o}C, while the higher temperature of operational TE materials is around 1300-1500 K [5]. We then optimize the interfacial temperature for least energy cost. The TE generator has received more attention as an engine for waste heat recovery, for which the temperature range is quite similar to that of steam turbines. This solid state device is also known as a moderate performance device due to the low efficiency of today's thermoelectric materials and the intrinsic thermal resistance that dissipates the heat energy loss. Thus only a space/weight limited application, such as vehicle exhaust heat recovery [6][7][8], has been heavily investigated so far, even though, the solid-state thermoelectric energy conversion is scalable to higher temperatures. This characteristic becomes an advantage which other technologies could not accommodate.

The TE module can be designed for optimum results by changing the element thickness to match the external thermal resistances as reported in our previous work [9]. A heat flow concentration inside of the TE module by making the fill factor smaller, yields a much less material mass necessary for the same power output per unit area as far as it maintains the internal thermal resistance match to the sum of external thermal resistances [10]. We also studied the thermal and electrical parasitic impacts [11] for the optimal design. A fill factor of approximately 10% shows a significant reduction of TE materials mass with reasonably smaller parasitic impacts. The optimum TE design in this study takes into account both the initial cost to build the combined system and the running cost of the fuel. Knowles and Lee [12] recently studied a combined system with a TE topping cycle on a higher temperature Brayton cycle gas turbine. In their report, efficiency at maximum power output was discussed. They point out that although a thermoelectric generator topping cycle enhances efficiency of Brayton for a low temperature turbine, efficiency cannot exceed a high temperature gas turbine. They suggest that using a TE topping cycle is limited to cases when space or price for a high temperature turbine cannot be justified. To consider the full energy cost, we optimized the design parameters for fuel economy and thus we can point out the broader advantages of TE topping cycle steam turbine as a function of operation time and fuel cost.

MODEL DEVELOPEMENT

The thermal circuit model of the TE and Rankine cycle combined system is shown in Fig. 1. We assumed the heat flux q_{in} is not limited to a specific range and the source temperature T_{s} and the thermal ground temperature T_{a} (room temperature) are fixed. More specifically, T_s is the adiabatic flame temperature of the fuel. T_g is the interfacial temperature between the two engines. The power output from the TE is extracted at the external electrical load R_{L} in an electrical circuit connected to the element. Due to the Seebeck effect created by the temperature difference between T_{h} and T_{c}, the electrical current j goes through the TE element and connected R_{L}. The power output from TE is described as a function of the design parameter d, which is the thickness of thermoelement and directly connected to both the thermal and electrical performances. We always assume heat flow and system design per unit area in the analysis.

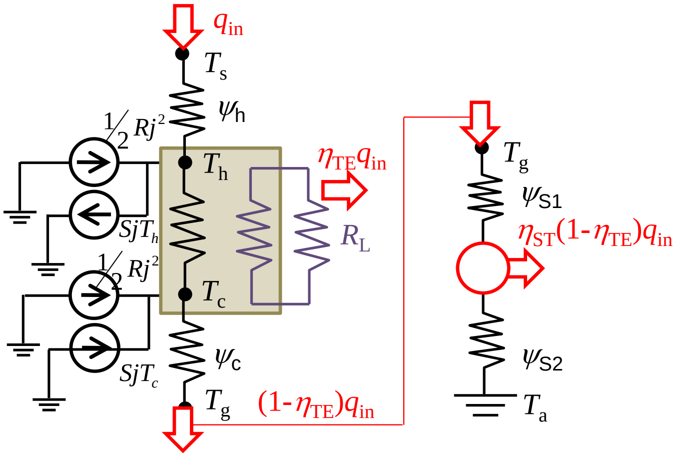

Figure 1: Thermal network model of the combined system with TE on top (left hand side of diagram) of the ST (right hand side). Left side shows the TE part and The electrical circuit of TE is adjacent to the thermal resistance of TE element (in a dark block region).

At the TE section, the external thermal resistances ψ_h and ψ_c are assumed to be symmetric. This is convenient for simplifying the equation. Also, the power output is insensitive to asymmetric thermal contacts with hot and cold reservoirs over a range several times the ratio between the two thermal resistances $\psi_h \cong \psi_c$. According to [9], the temperature relation is described as a function of leg thickness as

$$\frac{(T_h - T_c)}{(T_s - T_g)} = \frac{d}{d + m\beta\sum\psi} = \frac{d}{d + d_0} \qquad (1)$$

where, d is the element thickness, d_0 is the optimum thickness for the maximum power output. m is the electrical resistance ratio of the load resistance against the internal resistance. T_h and T_c are the hot side and the cold side temperature of the thermoelement, respectively. According to thermal and electrical impedance matching,

$$d_0 = m\beta\sum\psi \qquad (2)$$

while,

$$\sum\psi = \psi_h + \psi_c \qquad (3)$$

and

$$m = \sqrt{1 + Z\overline{T}} \qquad (4)$$

$Z\overline{T}$ is a dimensionless figure-of-merit of a thermoelectric material while $\overline{T}$ stands for a mean operating temperature across the TE leg and Z contains material properties, i.e. thermal conductivity β, electrical conductivity σ, and Seebeck coefficient S , in relation as

$$Z = \sigma S^2/\beta \qquad (5)$$

Power output per unit area w is found for T_h and T_c, as

$$w_{TE} = \frac{m\beta Z(T_h - T_c)^2}{(1+m)^2 d} \qquad (6)$$

Then the efficiency η_{TE} is found as

$$\eta_{TE} = \frac{w}{q_{in}} = \frac{m\beta Z(T_h - T_c)^2}{(1+m)^2 d}\,\frac{1}{(T_s - T_h)/\psi_h} \qquad (7)$$

To investigate a general trend, we make a coarse assumption that (T_s - T_h) and (T_c - T_g) are approximately equal. Then Eq. (6) and (7) can be rewritten as,

$$w_{TE} = \frac{Z}{(1+m)^2}\,\frac{d/d_0}{(d/d_0 + 1)^2}\,\frac{1}{\sum\psi}(T_s - T_g)^2 \qquad (8)$$

$$\eta_{TE} \cong \frac{Z}{(1+m)^2}\,\frac{d/d_0}{(d/d_0 + 1)}(T_s - T_g) \qquad (9)$$

These are functions of the dimensionless thickness d/d_0 with given conditions $\Sigma\psi$, T_s, and T_g. An extremely thin thermoelement generates nearly zero output and the extremely thick thermoelement also generates nearly zero output according to Eq. (8).

The energy production cost for the thermoelectric section Y_{TE} [\$/kWh] is calculated as follows.

$$Y_{TE} = \frac{I_{TE}}{hw_{TE}} + \frac{Y_f}{\eta_{TE}} \tag{10}$$

where, h is hours of operation, Y_f is the cost of potential chemical energy of the fuel in units of \$/kWh, and I_{TE} is the initial material cost to build the system, given by

$$I_{TE} = \rho dFG + 2\rho_s d_s G_s \tag{11}$$

where, subscript s stands for the substrates of thermoelectric modules, ρ is density, F is fill factor, and G is the material market unit price [\$/kg]. Heat sinks are not included in this part of the model, since they are already included in the Rankine cycle unit. We may replace them with modified versions but do not expect a different price, thus we did not double count the heat sink in Eq. (11).

The first term of the right hand side of Eq. (10) is the payoff for a one time initial investment of the generator and involves power output performance. This initial cost is amortized over the operating hours. The second term is the operating cost that directly depends on the fuel cost and the energy conversion efficiency. Therefore, there must be the global optimum in between the maximum efficiency and the maximum power output. As Eqs. (8) and (9) show, these are tightly related.

Substituting Eqs. (8), (9), and (11) into Eq. (10), the energy production cost is found as a function of TE leg thickness, d. For the further simplification, we assume the ratio of the element thickness and the substrate thickness d/d_s is a constant. Replacing d/d_0 with x, the energy production cost becomes,

$$Y_{TE} = \frac{\left(\rho FG + 2\rho_s cG_s\right)\left(1+m\right)^2 d_0 \left(x+1\right)^2}{hZ\left(T_s - T_g\right)^2} \sum_{TE} \psi + \frac{\left(1+m\right)^2 \left(x+1\right)}{Zx\left(T_s - T_g\right)} Y_f \tag{12}$$

OPTIMIZATION

By taking the derivative of Eq. (12), $\frac{\partial}{\partial x} Y_{TE} = 0$, we find the value of x that will minimize Y_{TE}. The solution is found as Eq. (13) which is the only real formula among the possible three solutions.

$$x = \frac{1}{3}\left(X + \frac{1}{X} - 1 \right) \tag{13}$$

while giving the macro parameter X as,

$$X = \frac{\sqrt[3]{2}A}{\sqrt[3]{-2A^3 + 27A^2 B + 3\sqrt{3}\sqrt{27A^4 B^2 - 4A^5 B}}} \tag{14}$$

with assigning A and B as,

$$A = 2\frac{\left(\rho FG + 2\rho_s cG_s\right)\left(1+m\right)^2 d_0}{hZ\left(T_s - T_g\right)^2} \sum_{TE} \psi\,, \quad B = \frac{\left(1+m\right)^2}{Z\left(T_s - T_g\right)} Y_f \tag{15}$$

The Rankine cycle in this work considers a simpler model, which is comprised of an ideal engine and the irreversible thermal contacts for the hot side ψ_{S1} and the cold side ψ_{S2}, respectively. The efficiency relative to thermodynamic limit (Carnot efficiency) of the Rankine cycle is assumed to change by the flow rate of steam independent of the steam temperature. The work generated by the turbine is considered as electrical power. The efficiency of the turbine includes the mechanical efficiency and the conversion efficiency from dynamic energy to electricity. It is reasonable to assume that the efficiency follows the Carnot efficiency with a coefficient C_{ST}, $\eta'_{ST}/C_{ST} = \eta_{ST}$.

$$Y_{ST} = \frac{Y_i}{h}\frac{W_{ST\_\max}}{w_{ST}} + \frac{Y_f}{C_{ST}\eta_{ST}} \tag{16}$$

$$w_{ST} = \frac{1}{\sum_{ST}\psi} \frac{\eta'_{ST}/C_{ST}\left(T_g - T_a - T_g\,\eta'_{ST}/C_{ST}\right)}{1 - \eta'_{ST}/C_{ST}} \tag{17}$$

$$w_{ST\_\max} = \frac{1}{\sum_{ST}\psi}\left(T_g - 2\sqrt{T_a T_g} + T_a\right) \tag{18}$$

Substituting into Eq. (16),

$$Y_{ST} = E\frac{\left(A - \eta'_{ST}\right)}{\left(B - C\eta'_{ST}\right)\eta'_{ST}} + \frac{D}{\eta'_{ST}} \tag{19}$$

where the local variables A, B, C, D, and E are,

$$\begin{gathered} A = C_{ST},\ B = \left(T_g - T_a\right)C_{ST},\ C = T_g, \\ D = Y_f,\ E = \frac{Y_i}{h}\left(T_g - 2\sqrt{T_a T_g} + T_a\right)C_{ST} \end{gathered} \tag{20}$$

Similar to the thermoelectric engine, we find the efficiency. The solution is found as,

$$\eta_{ST}{}' = \frac{\left(AE + BD\right) - \sqrt{\left(AE + BD\right)^2 - B\left(CD + E\right)\left(AE + BD\right)/C}}{\left(CD + E\right)} \tag{21}$$

ANALYSIS

The following is a set of parameters used for the analysis. Adiabatic flame temperature is T_s = 2250 [K] from [13] and the ambient temperature is T_a=300 [K]

Performance factors of the systems are:

Thermal resistances ψ_h and ψ_c = 0.01 [K/W]
Thermal resistances in Steam Turbine system (heat sinks) $\psi_{S1} = \psi_{S2}$: pseudo defined [K/W]

TE baseline material properties, referred as the material ZT is unity in the later discussions:

Thermal conductivity β = 1.5 [W/mK]
Electrical conductivity σ = 25000 [1/Ω.m]
Seebeck coefficient $S = 2\text{x}10^{-4}$ [V/K]
Density ρ = 8200 [kg/m^3]
TE Fill factor = 10% (fractional area coverage)

ST performance constant C_{ST} is assumed 60%.

Cost factors common for the materials are:

TE material price 500 [$/kg]
ST machine cost 7000 [$/kW] based on [14]
Fuel cost 0.108[$/kWh]

We assumed the thermoelectric material based on a typical Bi2Te3 for material properties and the cost and extrapolated the electrical properties with fixing thermal conductivity to match to the targeting operating temperature.

The fuel cost above is calculated based on the market prices of gasoline and natural gas as well as the calorific value of the fuels from [15]. Interestingly the price for calorific value was similar for gasoline and LPG. This cost value is also the bottom line (minimum) for the electricity supply cost. As far as burning fuel, the electricity cost cannot be lower than this value, 0.108$/KWh.

i) Topping TE

The initial (h=0) maximum power output is found at d=d_0 [9]. A thicker leg ($d >> d_0$) leads a larger efficiency but lower power output since the thicker leg significantly limits the available heat flow for the temperature constraints. As increasing the operation hours, the optimum dimensionless thickness increases. It is because the higher efficiency is required for lowering the overall energy cost.

ii) Steam turbine

Fig. 2 shows the energy production cost as a function of the operating efficiency with varying the hours of operation of Rankine cycle steam turbine. At the very beginning, the energy production cost is higher since it is dominated by the initial investment of generator. As the operating hours increase, the minimum energy production cost decreases. The efficiency at this minimum cost gradually shifts as increasing the operating hours. A longer hour of operation tends to yield the design to match higher efficiency, while the system produces power lower than the maximum potential.

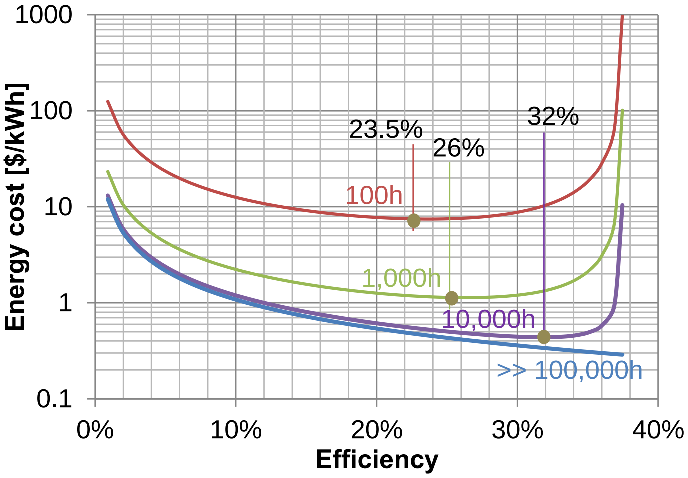

Figure 2: Energy cost vs. operating efficiency of ST. T_g=800 K

RESULT AND DISCUSSION

i) Power output

Fig. 3 shows result of combined system. The power output optimized for minimum energy cost is shown as a function of the interface temperature T_g. The total power output and its TE part and the ST part are also shown. By the power output against the hours of operation analysis, the TE part hits the maximum at approximately 1000-2000 hours of operation and slightly decreases as the hours of operation increases as detailed in [16]. The optimum thickness of the TE leg becomes thicker as the interface temperature increases. It gives a significant impact on ST power output by adding TE on top of it compare to ST alone. The heat flow coming into the ST part is limited by the temperature constraint and TE leg thickness. The relation above gives a peak power output for the combined system. The maximum power output is observed at 728 K for the design of 10,000 hours operation while the maximum of ST part is found at 974 K without giving any practical limitations. The optimum steam temperature 728 K is quite high, but it is available for superheat steam turbines. Considering the result of TE topping Brayton cycle [12] suggests that our results could cover the range from steam turbine to the transitional region to Brayton cycle.

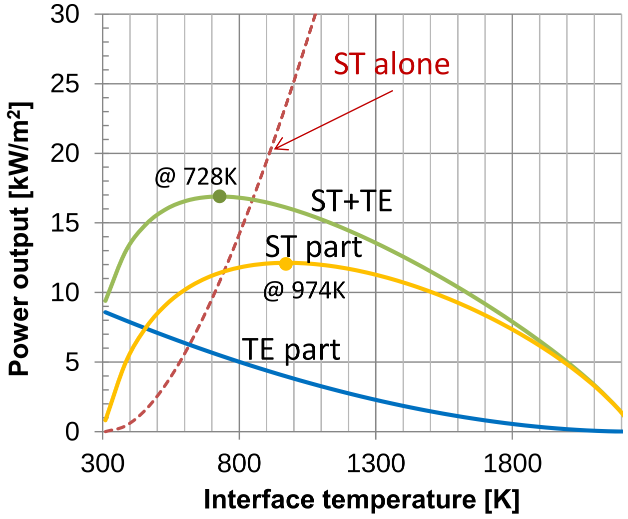

Figure 3: Optimum power output for the lowest energy cost as functions of interface temperature at 10,000 hours of operation.

ii) Efficiency

Fig. 4 shows the efficiency of the energy production as functions of interface temperature T_g. The combined system is optimized for lowest energy cost at 10,000 hours of operation. The trade-off relation between TE and ST gives a system characteristic, which increases efficiency by increasing temperature and it gradually saturates in higher temperature for baseline ZT=1. As increasing the figure-of-merit (ZT) of the TE material, the maximum efficiency of TE part significantly increases. This impact is much more than at the maximum power optimum.

There is no optimum interface temperature for ZT=1 for this case. As ZT increases to ZT=2, the optimum interface temperature is observed and the temperature shifts to lower as ZT further increases. We also investigated the impact of changing the material properties (see Eq. 5) of the figure-of-merit (ZT) individually. The impact of decreasing thermal conductivity (solid curves) is more influential than increasing power factor (dashed curves). The impacts of either electrical conductivity or Seebeck coefficient are exactly the same. It is also supported by Eq. (12) with careful investigation.

If T_g is close the ambient temperature, the energy production cost [\$/kWh] significantly changes. As efficiency curves increases as T_g increases in Fig.4, the energy cost decreases as T_g increases. At 454K of temperature and 15% of efficiency, a cross over point is observed between TE-alone and ST-alone for 10,000 hours of operation. In earlier hours, the cross over temperature is found in higher range.

iii) Energy production cost

The first term of the Eq. (12) depends on the operation hour. The energy cost is dominated by the first term during the small initial hours and exponentially decay as operation runs longer hours. If any improvement employed for ZT, increasing figure-of-merit reduces the energy cost as expected. In particular, decreasing thermal conductivity dramatically lowers the energy cost in the early operation as the first term $(x+1)^2$ makes an impact. For longer time operation, the second term does not make a significant difference between changing thermal conductivity and changing electrical conductivity or Seebeck coefficient.

Total cost in certain operation hours is shown in Fig 5. The minimum energy cost for a particular hours-of-operation is found. It is coincidence that the optimum design temperature T_g is found near the maximum allowable steam temperature for practical ST. The bottom dashed curve in Fig. 5 shows the minimum energy cost if the combined system could operate for infinity hours.

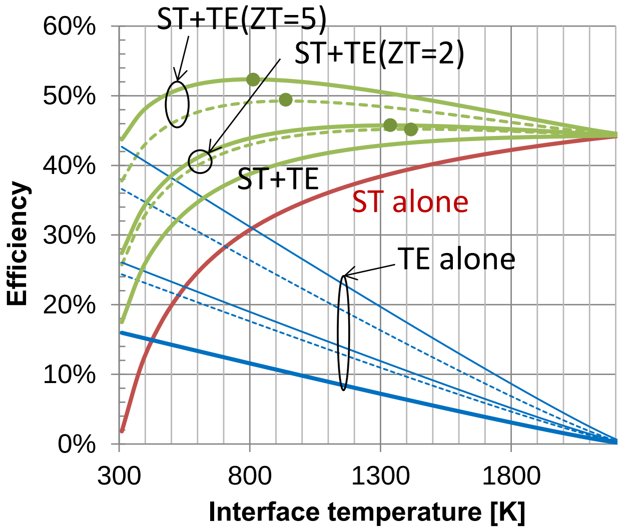

Figure 4: Efficiency as a function of interface temperature for ZT=1 baseline and the TE and total efficiency for ZT=5 and ZT=2 are also shown. Dashed curves correspond to the change in power factor and solid curves correspond to the change in thermal conductivity for ZT improvement. Dots on the ST+TE curves indicate the peak efficiencies, which are (1340 K, 1430 K) and (805 K, 941 K) for of ZT=2 and ZT=5 by changing (power factor, or thermal conductivity), respectively.

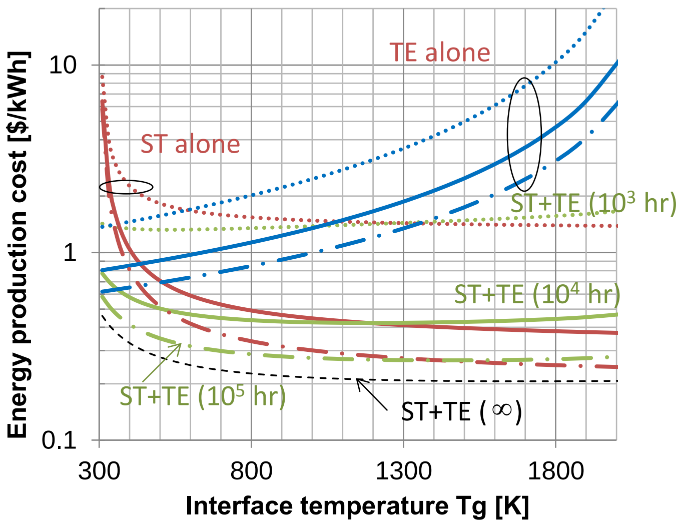

Figure 5: Energy production cost of the combined system with TE alone and ST alone against steam temperature T_g. Dotted curves show 1000 hours, solids curves show 10^{+4} hours, and broken curves show 10^{+5} hours of operations. The bottom dashed curve shows the minimum cost.

CONCLUSIONS

We discussed the combined power generation system with a TE on top of a Rankine cycle ST, while the TE materials are available in operation at up to around 1500K as the highest temperature. We developed a generic model and analyzed energy economy. The optimum design/operation for the lowest energy cost both for TE and ST are analytically found. The advantage of the combined system was demonstrated while both always minimize the payback of initial cost. The optimum balance of the design/operation point between the maximum power and the maximum efficiency depends on the hours-of-operation. Another factor for optimizing the system is the interface temperature between the two generators. A higher interface temperature lowers the energy cost, but there is a practical temperature limitation by structural material concerns of turbines. Improving thermoelectric figure-of-merit (ZT) is another key to increase power output and efficiency. We also investigated the impacts of changing thermoelectric properties and showed the different impact of power factor and thermal conductivity for the same ZT. The best balance between the lowest fuel consumption and the maximum power output is found at around 800K for interface temperature for 10,000 hours of operation. In summary, the combined system enhances the energy economy by effectively reusing a large amount of heat losses that would otherwise occur in a standalone Rankine cycle steam turbine. .

ACKNOWLEDGMENTS

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