Advanced Thermoelectric Power System Investigations for Light-Duty and Heavy Duty Applications: Part I

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ABSTRACT

The U.S. Department of Energy's National Renewable Energy Laboratory (NREL) has developed an integrated heat exchanger/thermoelectric power system analysis tool (in Matlab/Simulink environment) that simultaneously analyzes and optimizes the integrated effects of heat exchanger and thermoelectric power generator (TEPG) performance in light-duty-passenger (LDP) and heavy-duty (HD) vehicle waste heat recovery applications. Part I of this two-part paper describes the mathematical basis of this analysis approach as applied to TEPGs using single-material and segmented-leg thermoelectric (TE) couples. The integrated system analysis approach to heat exchanger / TEPG system performance allows NREL to simultaneously quantify the effects of important system design parameters, and heat exchanger and TEPG device design details on performance and power output in LDP and HD vehicles of interest. Part I discusses system power maximization, potential electrical power available, and cold side cooling mass flow requirements in LDP vehicle exhaust heat recovery applications. The model has been used in Part II of this technical paper to: (1) further investigate the behavior and interdependence of important thermal and TEPG system design parameters, and (2) predict potential TE system power output for a variety of thermal conditions in LDP and HD vehicles.

NOMENCLATURE

English

A_p - p-type element area [m^2]
A_n - n-type element area [m^2]
C_p - Specific heat [J/kg-K]
f_n - Function as derived from TE equations in Angrist [2] and Heikes and Ure [3]
I - Device current [A]
L - TE element length [m]
$\dot{m}_c$ - Cold-side (Ambient) mass flow rate [kg/sec]
$\dot{m}_h$ - Hot-side (Exhaust) mass flow rate [kg/sec]
N - Number of couples
P - Device power [W]
q_h - Hot-side thermal energy transfer
q_c - Cold-side thermal energy transfer
$R_{th,c}$ - Cold-side thermal resistance [K/W]
$R_{th,h}$ - Hot-side thermal resistance [K/W]
T_{amb} – Ambient temperature [K]
T_{exh} – Exhaust gas temperature [K]
T_h - TE hot side temperature [K]
T_c - TE cold side temperature [K]
UA - Effective Heat Exchanger Conductance * Area [W/K]
V - Device voltage [V]

Greek

ΔT_c – Cold-side temperature difference [$T_c - T_{amb}$] [K]
ε_c - Cold-side heat exchanger effectiveness
ε_h - Hot-side heat exchanger effectiveness
η - Thermoelectric conversion efficiency
λ_p - p-type element aspect ratio, L/A_p [m^{-1}]
λ_n - n-type element aspect ratio, L/A_n [m^{-1}]
σ - Heat loss factor – percentage of interface input heat

Superscripts

* - optimum or maximum efficiency conditions

Subscripts

c - Cold-side of TE device
h - Hot-side of TE device
ex - Refers to hot or cold side heat exchanger
i - n- or p-type element specification
loss – Heat loss at a given point in the system
TE – TE device
in - Heat flow in
out – Heat flow out

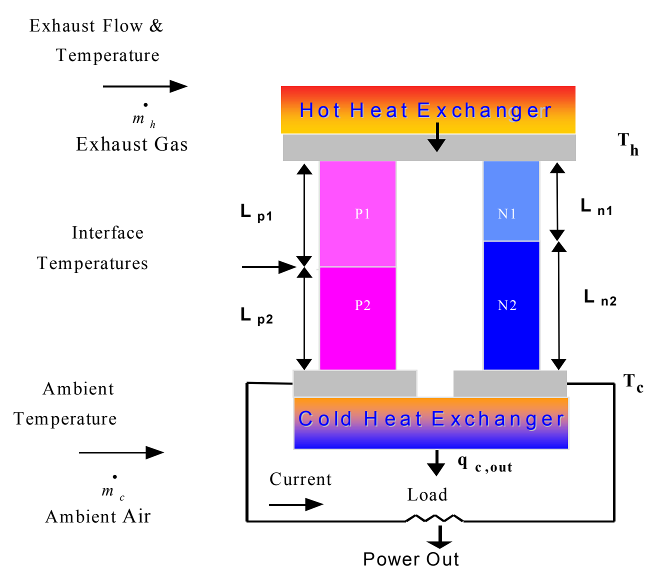

Figure 1 - Heat Exchanger / Segmented-Leg TE Device Configuration Schematic

INTRODUCTION

Future vehicles must possess significantly improved fuel economy and lower emissions to satisfy updated supplemental federal test procedure (SFTP) requirements in the United States and similar requirements in foreign countries. Direct thermal energy recovery/conversion technologies are receiving more research attention in order to recover waste thermal energy in advanced vehicles, convert it to useful high-grade electrical energy onboard the vehicle, and assist in increasing overall vehicle energy efficiency. Current estimates of available waste thermal energy from light-duty vehicle systems range from 20kW to 400 kW depending on engine size and engine torque-speed conditions. Current waste energy assessments indicate that the energy equivalent of 45 billion gallons of gasoline annually is transported down the exhaust pipes of the 240 million light-duty passenger (LDP) vehicles nationwide. Easily accessible vehicle systems that provide significant opportunities for and benefits from thermal energy recovery, operate at system temperatures from 500°C up to 900°C in light duty vehicles. Easily accessible high temperature systems in HD vehicles operate at 500°C to 650°C. The major desirable characteristics of energy conversion technologies would be completely solid state, no noise, no vibration, no moving fluids, high reliability, and low cost. Thermoelectric power generation (TEPG) systems, using advanced next-generation thermoelectric (TE) materials, currently hold the most promise for satisfying these requirements.

The U.S. Department of Energy's (DOE) National Renewable Energy Laboratory (NREL) has developed an integrated heat exchanger / TEPG system analysis tool (in Matlab/Simulink environment) that:

1) Simultaneously analyzes the interdependent effect of heat exchanger performance and TE device performance,
2) Simultaneously optimizes the heat exchanger/TEPG system to obtain the highest TEPG system efficiency and power output in any vehicle waste heat recovery application,
3) Can analyze segmented-TE-material designs and single-TE-material designs, quantum-well designs, and thin-film super-lattice designs,
4) Outputs the optimum design parameters as a function of TEPG hot side and cold side temperatures, and
5) Has been integrated with NREL's ADVISOR to provide TEPG/heat exchanger optimum design parameters for any vehicle configuration and drive cycle.

Figure 1 schematically illustrates the integrated heat exchanger / segmented-leg TEPG device configuration analyzed in this work. A hot-side exchanger typically extracts thermal energy from a gas flow (i.e., vehicle exhaust stream) and transfers that energy into the TEPG device; a fraction of the energy is converted to electrical power; and the remaining thermal energy is dissipated to the environment via a cold-side heat exchanger.

HEAT EXCHANGER / THERMOELECTRIC ANALYSIS MODELS

The newest advanced TE materials research proposes TEPG system designs that use p-type and n-type legs containing an advanced single TE material, or two to three TE materials in advanced segmented-leg TE designs. NREL's thermoelectric analysis models are structured to analyze and identify optimum TEPG designs for both single-material-leg and segmented-leg TE designs. In the analysis, optimum power system designs, defined by maximum TE conversion efficiency conditions, are characterized by optimum TE parameter sets:

$$\left(\frac{V}{N}\right)^* = f_1(T_h, T_c) \quad [1]$$

$$(I \cdot \lambda)_i^* = f_2(T_h, T_c) \quad [2]$$

$$\left(\frac{q_h \cdot \lambda}{N}\right)_i^* = f_3(T_h, T_c) \quad [3]$$

$$\left(\frac{q_c \cdot \lambda}{N}\right)_i^* = f_4(T_h, T_c) \quad [4]$$

$$\left(\frac{\lambda_p}{\lambda_n}\right)^* = f_5(T_h, T_c) \quad [5]$$

$$\eta^* = f_6(T_h, T_c) \quad [6]$$

This optimum TE analysis methodology is described by Hendricks [1] and based on the TE design and performance optimization analyses discussed in Angrist [2] and Heikes and Ure [3] for single-material-leg TE systems. In segmented-leg TE systems, the analysis methodology is based on the analysis equations and approach described in Angrist [2], and TE design and performance optimization discussed in Swanson et al. [4]. This approach carefully considers segment interface heat flux and temperature matching within the TE couple, thermal interfaces between the heat exchange systems and TE device, and thermal losses within the heat exchangers and TE device.

Hot side thermal losses are parametrically characterized in this analysis by the relations:

$$q_{h,ex,loss} = \sigma_{ex,h} \cdot q_{h,ex} \quad [7]$$

$$q_{h,TE,loss} = \sigma_{TE,h} \cdot q_{h,in,TE} \quad [8]$$

where $\sigma_{ex,h}$ and $\sigma_{TE,h}$ represent heat loss fractions of the incoming thermal energy at respective interfaces (i.e., heat exchanger interface with environment and TE device/heat exchanger interface).

Cold side thermal losses are parametrically characterized in this analysis by the relations:

$$q_{c,ex,loss} = \sigma_{ex,c} \cdot q_{c,ex,in} \quad [9]$$

$$q_{c,TE,loss} = \sigma_{TE,c} \cdot q_{c,TE,out} \quad [10]$$

where $\sigma_{ex,c}$ and $\sigma_{TE,c}$ represent heat loss fractions of the outgoing thermal energy at respective interfaces (i.e., heat exchanger interface with environment and TE device/heat exchanger interface).

Heat losses are expressed parametrically for this analysis because the true temperature-dependent characterization of thermal losses (i.e., conduction, radiation, convection) is also very configuration dependent. Since the final system configuration is difficult to establish a priori, this system analysis needed some methodology that allowed one to parametrically determine the effect of heat losses on TEPG and heat exchanger design parameters and power output potential without knowing the exact heat losses for a specific configuration. The introduction of σ parameters provides a simplified mathematical approach to accomplish this from a system-level viewpoint. Of course, because the system heat losses are truly temperature dependent, the σ's are temperature dependent in real systems.

The system heat exchanger analysis is based on ε-NTU analysis methodology [5] with modifications for system thermal resistance effects. The system analysis incorporates similar heat exchanger analyses on both the hot-side and cold-side of the combined heat exchanger / TEPG system.

$$q_{h,TE} \cdot \left[\frac{1}{\dot{m}_h \cdot C_p \cdot \varepsilon_h \cdot (1-\sigma_{ex,h})} + R_{th,h} \right] = \left(T_{exh} - T_h\right) \cdot (1-\sigma_{TE,h}) \quad [11]$$

$$q_{c,TE} \cdot \left[\frac{1-\sigma_{ex,c}}{\dot{m}_c \cdot C_p \cdot \varepsilon_c} + R_{th,c} \right] = \frac{\left(T_c - T_{amb}\right)}{(1-\sigma_{TE,c})} \quad [12]$$

Equations 11 and 12 relate the heat exchanger design parameters and various loss factors to the hot side and cold side thermal transport in the TE device. T_h and T_c in Eqs. 11 and 12 are the actual hot side and cold side temperatures of the TE device.

Examining Eqs. 1-12 reveals that, given a specific ambient temperature (T_{amb}) and exhaust gas temperature (T_{exh}), this set of design parameter equations is a function only of T_h and T_c. Therefore, the optimum TE system and heat exchanger design parameter sets given by Eqs. 1-12 can be uniquely defined for given T_h and T_c conditions. Selecting two of the crucial TEPG system or heat exchanger variables then allows one to completely specify all the other TEPG system and heat exchanger design variables within Eqs. 1-12. The optimum TE and corresponding heat exchanger design parameters were investigated, and the results reported in the following discussions, for a variety of T_h and T_c conditions. The TEPG system voltage and hot-side heat exchanger mass flow rate were typically specified in the design studies, and all other system design variables were calculated from the parameter sets defined by Eqs. 1-12. This gave an integrated, comprehensive picture of the optimum TE and heat exchanger design parameters, and their interdependencies in optimized designs for LDP and HD vehicle power generation. This integrated heat exchanger / TEPG system analysis approach allows one to simultaneously evaluate: (1) accurate heat exchanger design and performance requirements, and (2) the true optimum TE design requirements and power generation performance possible in any given application.

ADVANCED THERMOELECTRIC MATERIALS

Advanced, next-generation TE materials developed in the past 5 years are providing enhanced opportunities for TE conversion systems with much higher TE conversion efficiencies and power outputs, and the promise of cost-effective waste thermal energy conversion in advanced vehicle systems. NREL is investigating system power benefits and system thermal integration challenges of using TEPG systems with various advanced, next-generation TE materials, such as skutterudites (p-type $CeFe_4Sb_{12}$; n-type $CoSb_3$), quantum-well materials, and thin-film superlattice materials, to recover waste thermal energy at various potential locations within LDP vehicles and HD trucks. Optimum design analyses were performed in Part I and Part II of this technical work for three advanced TE material combinations in three segmented-leg TE design configurations:

1) p-type $CeFe_4Sb_{12}$ / p-type Bi_2Te_3; n-type $CoSb_3$ /n-type Bi_2Te_3 [6]
2) p-type TAGS / p-type Bi_2Te_3; n-type 2NPbTe / n-type Bi_2Te_3 (Hi-Z Technology, Inc.)
3) p-type $CeFe_4Sb_{12}$ / Zn_4Sb_3 / p-type Bi_2Te_3; n-type $CoSb_3$ / n-type Bi_2Te_3 [6]

Single-TE-material-leg configurations have also been investigated, but no single-TE-material-leg configuration can produce the power output of interest (i.e., > 500 W) in any LDP or HD vehicle applications. Therefore, single-TE-material-leg results were excluded from this discussion.

POWER MAXIMIZATION EFFECTS IN LIGHT DUTY VEHICLE APPLICATIONS

Initial investigations centered on LDP vehicle applications in which typical exhaust gas mass flow rates are 0.01-0.03 kg/sec and typical exhaust gas temperatures are 600-700°C. Interactions between the hot-side heat exchanger and the TEPG system are critical to determining the optimum TE system design and the potential power generation possible in any such vehicle application. This interaction ultimately determines the hot-side temperature experienced by the TEPG system, and therefore its conversion efficiency, and the amount of thermal energy, q_h, delivered to the TEPG system. Similarly, the interaction between the cold-side heat exchanger and TEPG system ultimately determines the cold-side temperature experienced by the TEPG system and cooling requirements (i.e., mass flow rate) on the system cold-side.

Figure 2 demonstrates the interaction between the hot-side heat exchanger and TEPG system in determining the maximum power output in LDP exhaust waste heat recovery at various T_h and T_c combinations. These studies were performed for hot-side (exhaust gas) mass flow rates of $\dot{m}_h$ = 0.01, 0.02, and 0.03 kg/sec, which is typical of a LDP vehicle (i.e., automobile, minivan, or sport-utility-vehicle). The exhaust gas temperature in this case was 700°C (973 K), which is typical of exhaust gas temperatures at the catalytic converter in a light-duty vehicle. TE material combination #1 was used in this analysis. The TEPG system power output maximizes at certain hot-side temperatures due to the interaction between the amount of thermal energy, q_h, delivered to the TEPG system by the heat exchanger and the TE conversion efficiency. At low hot-side temperatures, the heat exchanger can supply large amounts of thermal energy, but the TE conversion efficiency is low. At high hot-side temperatures, the TE conversion efficiency is high, but the heat exchanger supplies only a small amount of thermal

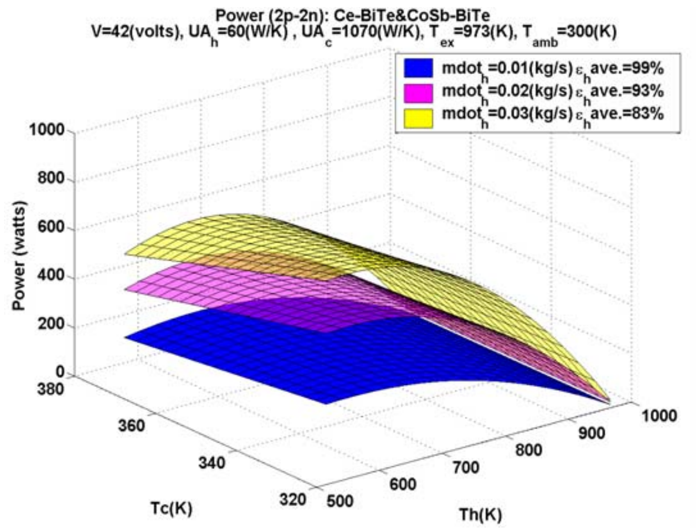

Figure 2 – Power Output vs. Temperature Conditions and Exhaust Mass Flow Conditions in LDP Vehicles Using TE Material Set #1.

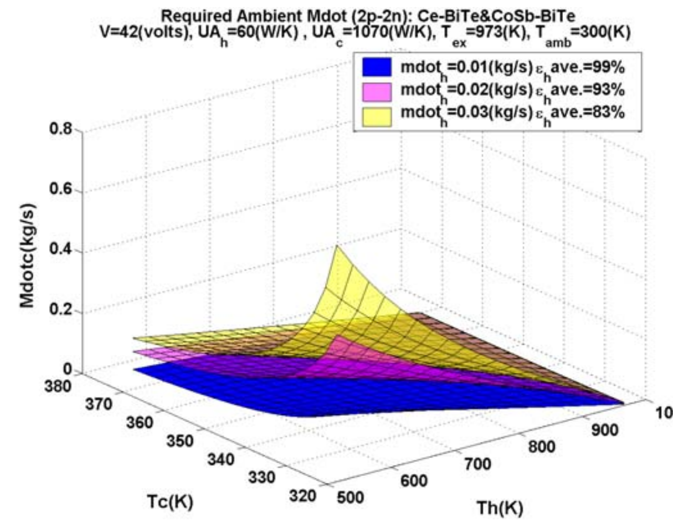

Figure 3 – Required Cold-Side Mass Flow Rate vs. Temperature Conditions and Exhaust Mass Flow Conditions Using TE Material Set #1.

energy. The "ridge of maximum power" for various cold side temperatures, T_c, is clear in Figure 2. Although maximum power does decrease as T_c increases, the impact of cold-side temperatures on power maximization is relatively small.

Figure 3 demonstrates the required system cold-side mass flow rates at various T_h and T_c combinations due to the interaction between the cold-side heat exchanger and the TEPG system. It is clear that the required cold-side mass flow rate can become extremely high (approaching 1 kg/sec), and completely system limiting, in certain T_h and T_c regimes. This situation can easily lead to thermal runaway conditions that ultimately decrease power output dramatically, and must be avoided in system design and operation. Examining Figs. 2 and 3 suggests that in certain T_h and T_c regimes it may be sound engineering design to back off the maximum power points to reduce required mass flow rates to more acceptable or preferred levels.

Figure 4 displays the results of additional TEPG system analyses performed using TE material combination #3. Comparing the power results in Figs. 2 and 4 shows that the maximum power generated for TE material combination #3 is about 60 watts larger than the power for TE material combination #1. Power outputs up to 0.9 kW appear possible in light-duty vehicles if a TEPG system using TE material combination #3 would be placed on the vehicle catalytic converter. Additional analyses indicate that somewhat lower power output (~0.7 kW) would be available if the TEPG system was located downstream of the vehicle's catalytic converter.

One critical conclusion from the results in Figures 2 and 4 is that, because of the power maximization effect, the hot side temperature of the TE device in these LDP applications actually will operate at approximately 600-650 K, even if the exhaust temperature is around 973 K. Consequently, TE material requirements (i.e., interface diffusion, thermal expansion, sublimation effects) may be somewhat relaxed from those one might expect by merely assuming the hot side temperature will be close to the exhaust temperature. Heat exchanger performance likely will not be high enough to supply the required hot side thermal flow to the TEPG device and simultaneously produce device hot side temperatures close to the actual exhaust temperatures.

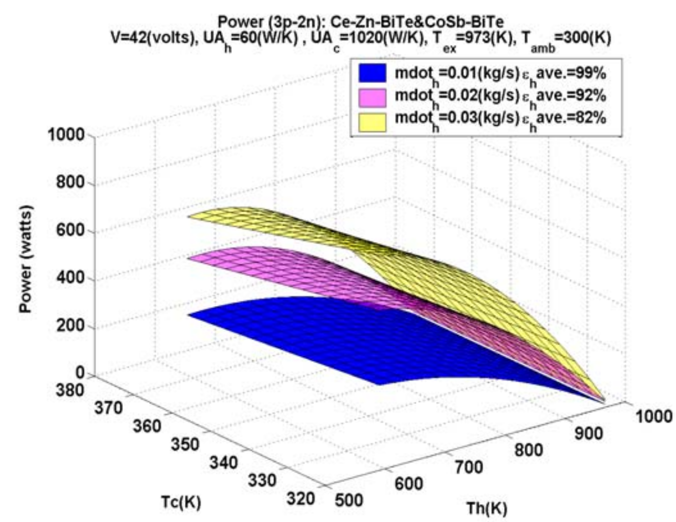

Figure 4 – Power Output vs. Temperature Conditions and Exhaust Mass Flow Conditions in LDP Vehicles Using TE Material Set #3.

DEVICE POWER–EFFICIENCY CHARACTERISTICS

System power and efficiency tradeoffs are important to the heat exchanger-TE device design. Figure 5 shows the typical system power/efficiency characteristic for a TE system using material set #1 and exhaust temperature, T_{exh} = 973 K. Lines of constant hot side temperature are shown in Figure 5 for reference in comparing system designs. The maximum system power point is clearly quite different than the maximum efficiency point. While it is quite clear from a system power perspective that one does not necessarily want to design to the maximum efficiency, it is critical to understand the exact behavior of the system power versus efficiency tradeoff so that intelligent system design assessments and decisions can be made. Figure 5 shows that small compromises in system power can create significant increases in device efficiency and therefore more efficient energy usage. These lower-power, higher-efficiency regions definitely represent preferred TE operating regimes that create more efficient and beneficial vehicle energy management.

Figure 6 demonstrates the system power/efficiency characteristics for a TE system using material set #3 and exhaust temperature, T_{exh} = 973 K. A similar system power/efficiency tradeoff behavior exists in this case, but system powers and device efficiencies are generally higher using this TE material set since it uses a 3 material segmented p-leg. Figures 5 and 6 also show that there are specific hot side temperature ranges associated with the preferred TE power – efficiency operating regimes.

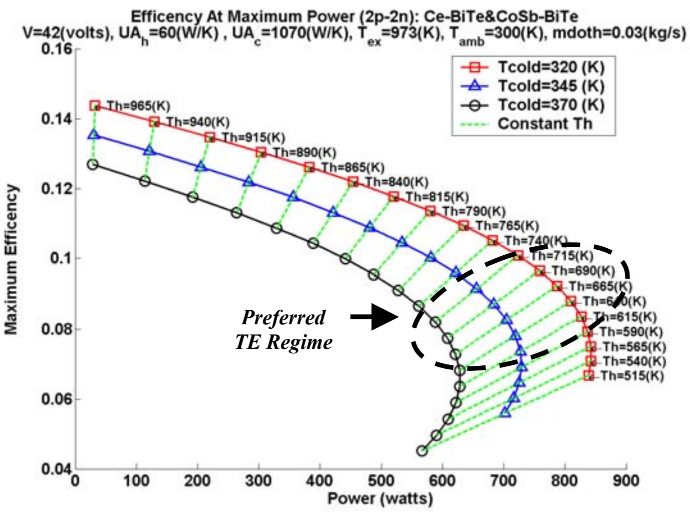

Figure 5 – System Power/Efficiency Characteristics in LDP Applications Using TE Material Set #1.

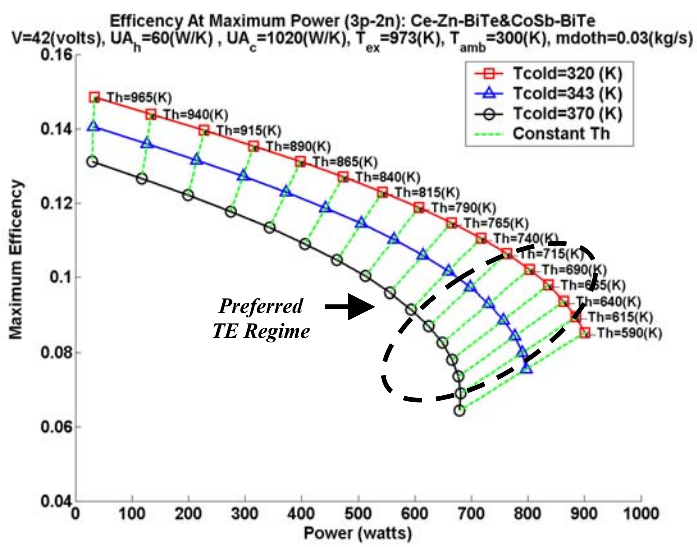

Figure 6 – System Power/Efficiency Characteristics in LDP Applications Using TE Material Set #3.

CONCLUSIONS

The U.S. Department of Energy's National Renewable Energy Laboratory (NREL) has developed an integrated heat exchanger/thermoelectric (TE) system analysis tool (in Matlab/Simulink environment) that simultaneously analyzes and optimizes the integrated effects of heat exchanger and thermoelectric device performance in LDP and HD vehicle applications. The integrated system analysis approach allows NREL to simultaneously quantify effects of important system design parameters on system performance and maximize system power output. The model has been used to: (1) investigate the behavior and interdependence of important TE and thermal system design parameters, and (2) predict potential TE system power output for a variety of thermal conditions in LDP and HD vehicles. The integrated system analyses are providing critical information on how much power would be available at various locations in the exhaust streams of LDP and HD vehicles.

The interaction of heat exchanger performance and TE device conversion performance creates critical system impacts on maximum TE system power output and cold side cooling requirements. System analysis results indicate that up to 0.9 kW of power appear possible in LDP vehicle exhaust applications, if the TEPG is placed on the vehicle catalytic converter. Lower power output (~0.7 kW) appears possible if the system is placed downstream of the LDP vehicle catalytic converter. System analysis results also indicate that certain T_h and T_c regimes exist that create exorbitantly high, and possibly system limiting, cold side mass flow requirements. These temperature regimes must be avoided when designing and implementing currently-envisioned, advanced TEPG systems in LDP exhaust heat recovery applications. There also exist preferred TE power-efficiency operating regimes, with associated hot side temperature ranges, that create more efficient vehicle energy management because of higher TE device efficiency. Finally, the analytic results also show that maximum TEPG system power actually occurs at TE system hot side temperatures of 600-650 K, because of the interaction between heat exchanger performance and TE device performance. This temperature level would provide significant relief on the thermal requirements (i.e., survival temperatures, thermal diffusion requirements, sublimation requirements) for the TE materials in LDP exhaust heat recovery applications.

Significant system design challenges remain to implement the integrated heat exchanger / TEPG systems in LDP and HD vehicles. These include integration of such thermal energy recovery sub-systems into vehicle systems, thermal and electrical interface design, verifying the potential real-world performance benefits predicted in this work, and lowering system costs. Future work will focus on what locations within a LDP or HD vehicle provide the most power generation potential given waste energy and temperatures available, heat exchanger performance, and projected advanced TE material properties.

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