System Considerations in Waste Heat Recovery

Gang Chen

Department of Mechanical Engineering
Massachusetts Institute of Technology
Cambridge, MA 02139

Email: gchen2@mit.edu
http://web.mit.edu/nanoengineering
Energy Usage in US

Net Primary Resource Consumption ~97 Quads

Source: Production and end-use data from Energy Information Administration, Annual Energy Review 2002.
*Net fossil-fuel electrical imports.
**Biomass/other includes wood, waste, alcohol, geothermal, solar, and wind.
Waste Heat Source Temperature

Direct Energy Conversion Device Working Range (Back of Envelope)

Device Hot Side Temperature (°C) vs. Device Heat Flux (W/m²)

- Heat Flux (TE High)
- Thermoacoustics
- TPV
- Thermionics
Energy Conversion Efficiency

Zebarjadi et al., Energy & Env. Sci., 5, 5147, 2012
System Consideration

- How to collect heat?
- How to reject heat?
- What is system cost?
Thermoelectric Devices

Nondimensional Figure of Merit

\[ ZT = \frac{\sigma S^2 T}{k} \]

- Joule Heating
- Seebeck Coeff.
- Electron Cooling
- Reverse Heat Leakage
- Through Heat Conduction
Nanocomposite Synthesis

Increase interfacial scattering by mixing nano-sized particles.

Batch fabrication for large scale application.

Nano Bi$_2$Te$_3$

Materials ZT Improvements

From Z.F. Ren
Power and Cost Example

- Dimensions of TE elements: 1.5mm x 1.5 mm x 1.6 mm
- Material cost per power output ≈ 0.1 $/Watt
- Cost of TE material can be small relative to total system cost!
Vehicle Waste Heat Recovery

How Much We Can Really Recover? What Temperature Range?

Radiator: 1/3 Heat Wasted $T_{\text{hot}} \sim 80 \degree \text{C}$

Engine Driving Efficiency $\sim 20\%$

Exhaust: 1/3 Heat Wasted $\sim 600 \degree \text{C}$
Heat to Electricity Recovery from Gas Stream

- For thermoelectric devices, $T_H$ higher is better.
- However, maximum heat intercepted from hot gas stream, $mc_p(T_{h,i} - T_H)$, decreases with $T_H$. 

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Efficiency Expectations

- $T_{h,i}=600\,^\circ C$, $T_c=50\,^\circ C$
- Optimal Hot Side Temperature $\sim 270\,^\circ C$
Locally Optimized Systems

- 1-3% Absolute Efficiency
- 5-20% Fuel Saving
- Engineering Room
- Materials Development
- 10% Cogeneration System
Heat Rejection

\[ q = k \frac{\Delta T}{L} \approx 1 \frac{W}{m \cdot K} \frac{100 K}{L} \]

\[ q = 5000 \text{ W/m}^2 ; \ L = 20 \text{ mm} \]

- Too expensive!

- What are TE filling fractions
- What are insulation requirement
- What are heat sink requirement
- What are system cost

Current: \( T_{\text{air}} = 25 \degree C \)
\( T_{\text{hot}} \approx 400 \degree C \)
From Micro Watts to Giga Watts

Sensors

Stove

Furnace

Solar

Vehicles

Power Plants

Industrial Waste Heat

μW

W

kW

MW

GW

35 x 35 μm²
Solar Thermoelectric Power Generator (STEG)

\[ q = k \frac{\Delta T}{L} \approx 1 \frac{W}{m \cdot K} \frac{100 \ K}{L} \]

- \( q = 1000 \ W/m^2 \) (1 Sun); \( L = 100 \ mm \)
- \( q = 100,000 \ W/m^2 \) (100 Sun); \( L = 1 \ mm \)

Kraemer et al., Nature Materials, 10, 523, 2011
Segmented TE Device

Summary

- Waste heat is everywhere.
- System thinking is crucial, heat collection and rejection subsystems should be considered for successful deployment.
- Applications could also be where large entropy is generated.
- Excellent progress in materials, challenges are taking materials to devices and systems that can penetrate market.