Enhancing Heat Recovery for Thermoelectric Devices

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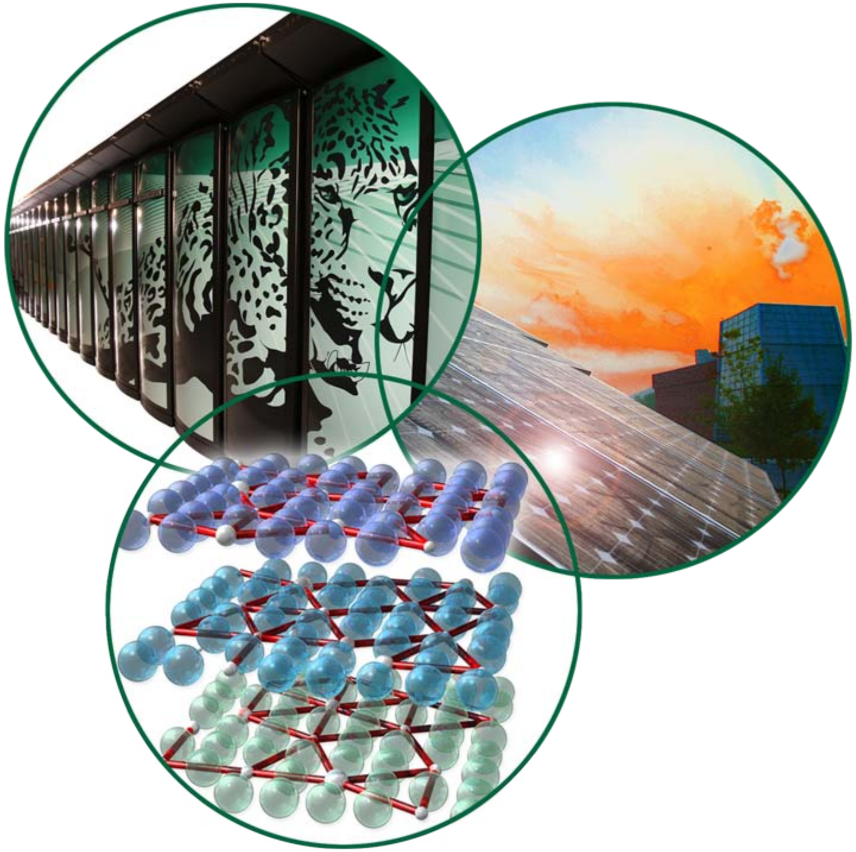
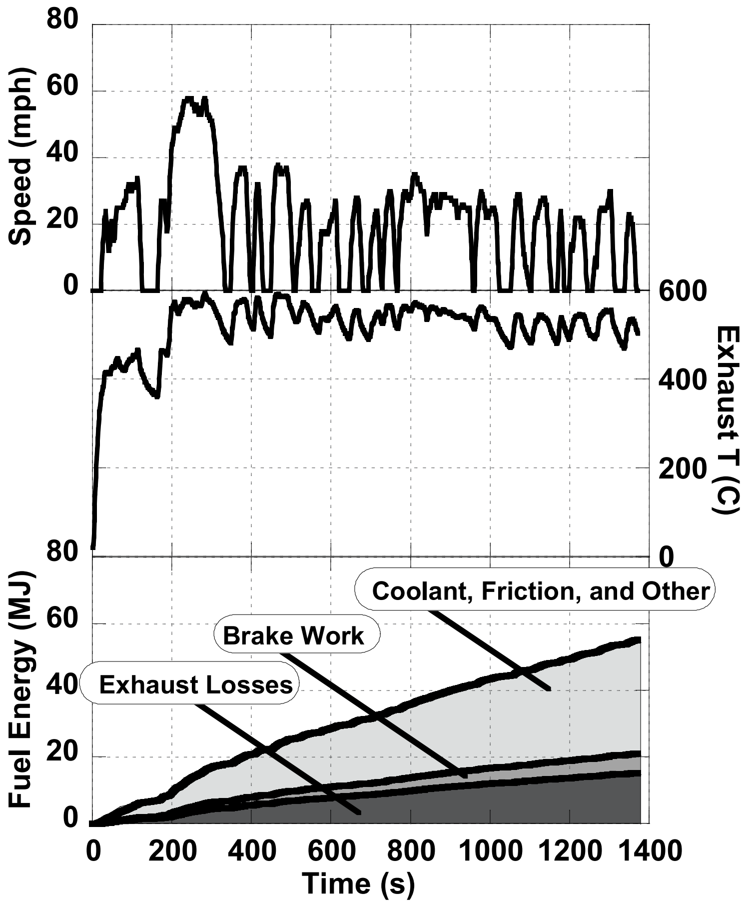
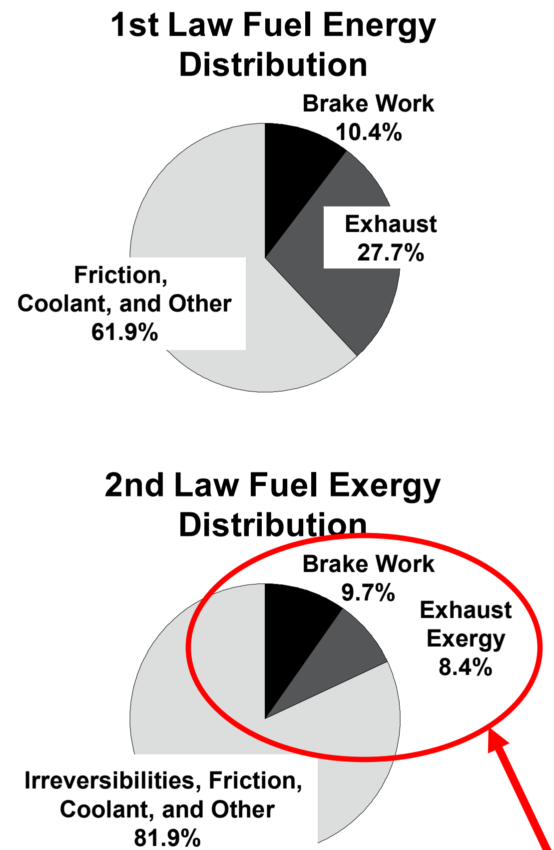


Motivation for exhaust heat recovery efforts

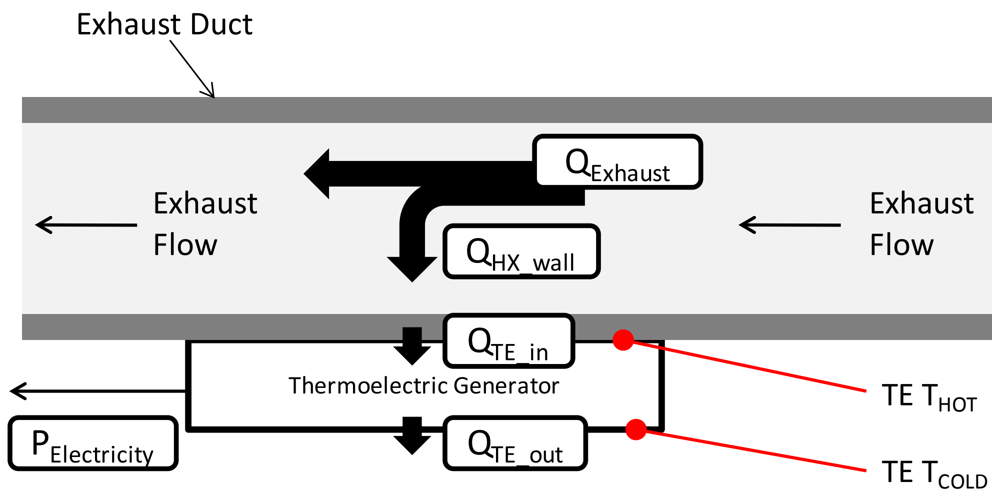




Federal test protocol (FTP) test cycle for a 2007 Saab Biopower showing speed, Experimental data were collected at the ORNL chassis dynamometer facility.

Availability of energy in exhaust is nearly as high as brake work

Basic heat recovery system for thermoelectrics

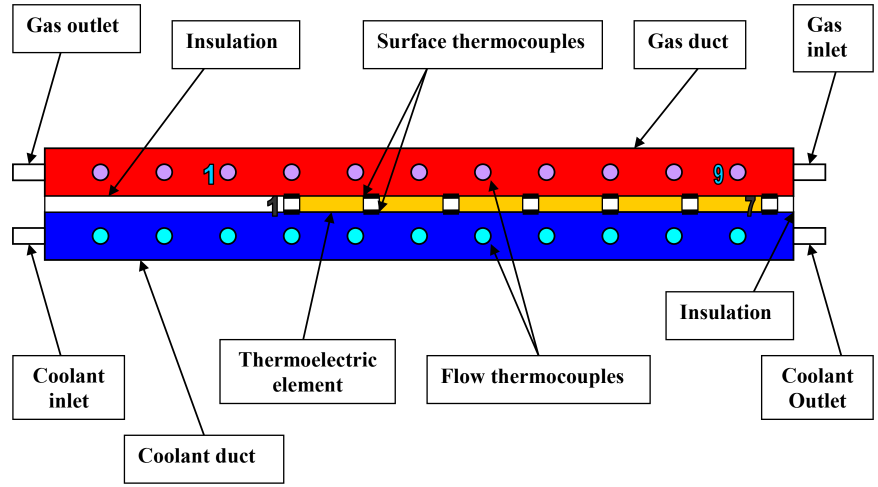


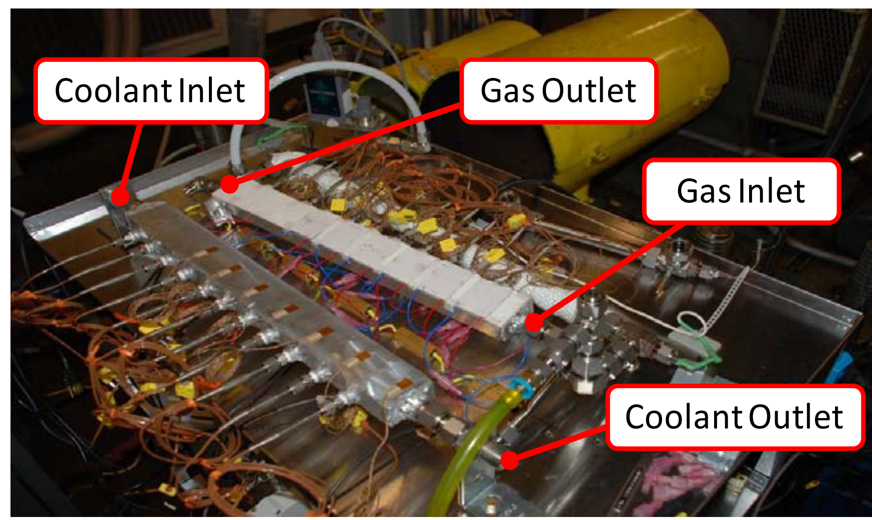
- **Electrical power generation dependent on temperature gradient across thermoelectric device**
  - **Thermoelectric temperature gradient is smaller than temperature gradient from bulk hot gas to bulk coolant**
- **Efficiency of thermoelectric heat recover system dependent on both heat exchanger and thermoelectric efficiency**

$$\eta_{System} = \frac{P_{Electricity}}{Q_{Exhaust}} = \eta_{Heat\_Exchanger} * \eta_{Thermoelectric}$$

ORNL Experimental Thermoelectric Apparatus

- Simulate exhaust flow with mass flow controller and intake air heater
- Two rectangular ducts for the hot and cold flows
- Each thermoelectric loaded with 5 Ohm power resistor
  - Voltage measured to record power
- Commercially available thermoelectric power generators from Marlow Industries
  - Thermoelectric material: Bi_2Te_3
  - ZT = 0.73





Experiments performed by visiting faculty during summer of 2009 and 2010

- Year 1 study
  - Parametric study of operating conditions
    - Simulated exhaust temperature
    - Simulated exhaust flow
    - Coolant temperature
  - Packed vs. unpacked duct
- Year 2 study
  - Multiport heat exchangers
  - Parametric study of operating conditions
  - Aluminum vs. stainless steel
  - Fouled vs. un-fouled heat exchangers

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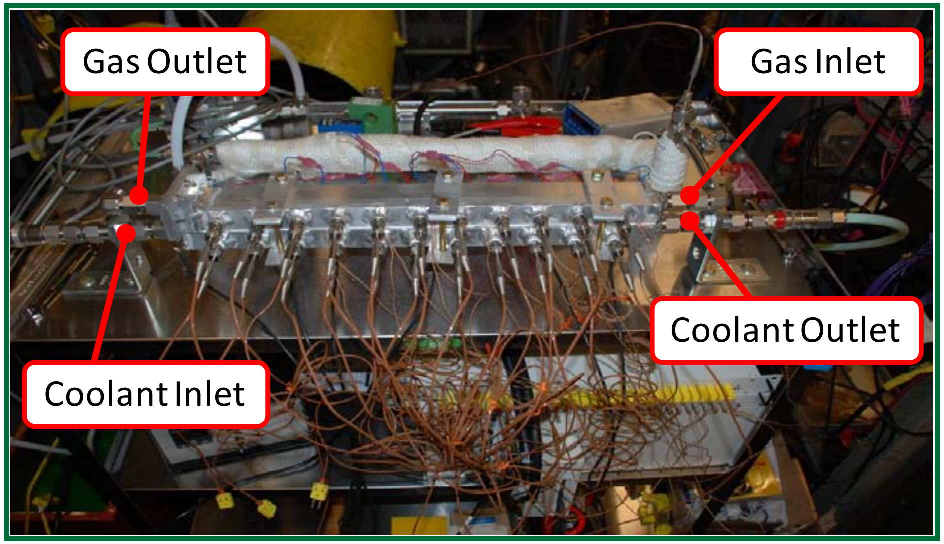
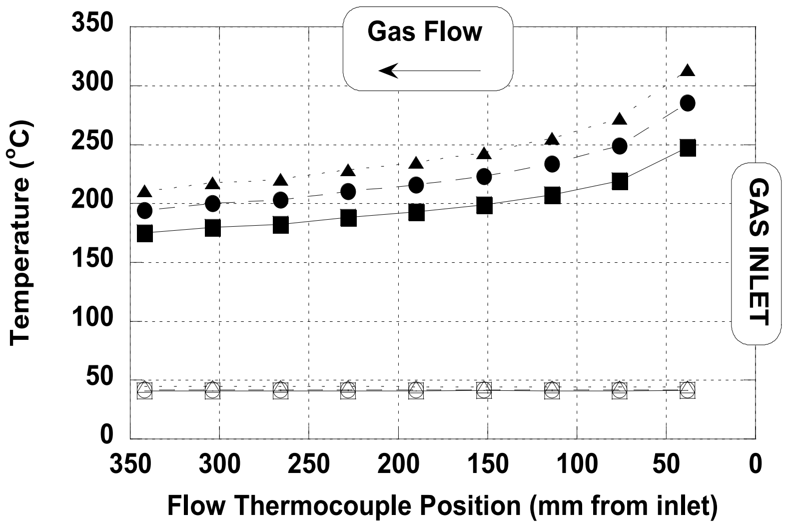
Year 1 Study

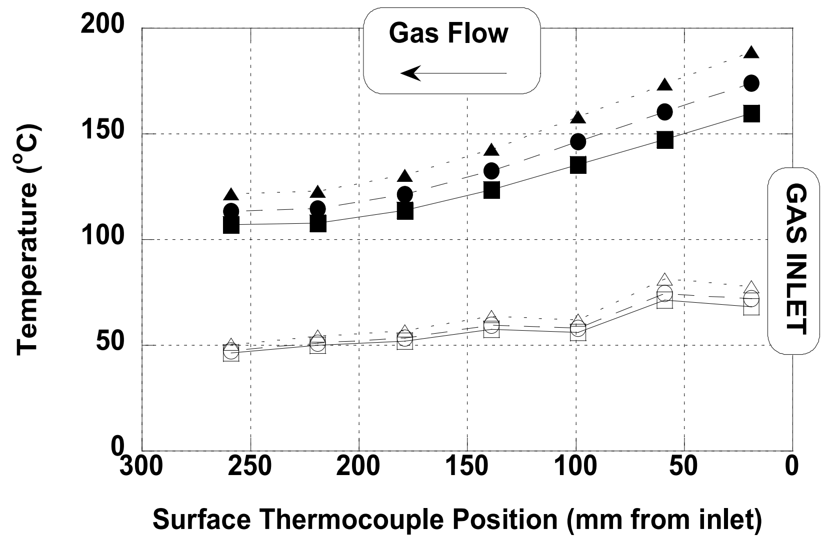
- Parametric investigation of operating conditions on thermoelectric performance
  - Simulated exhaust temperature and flow rate
  - Coolant temperature
- Enhancement of thermoelectric performance using duct packed with aluminum wool
- Journal article contains complete details

  Ibrahim, E.A., Szybist, J.P., Parks, J.E. Enhancement of automotive exhaust heat recovery by thermoelectric devices. *Proc. IMechE, Part D: J. Automobile Engineering*, 2010, 224(D8), 1097-1111. DOI 10.1243/09544070JAUTO1438



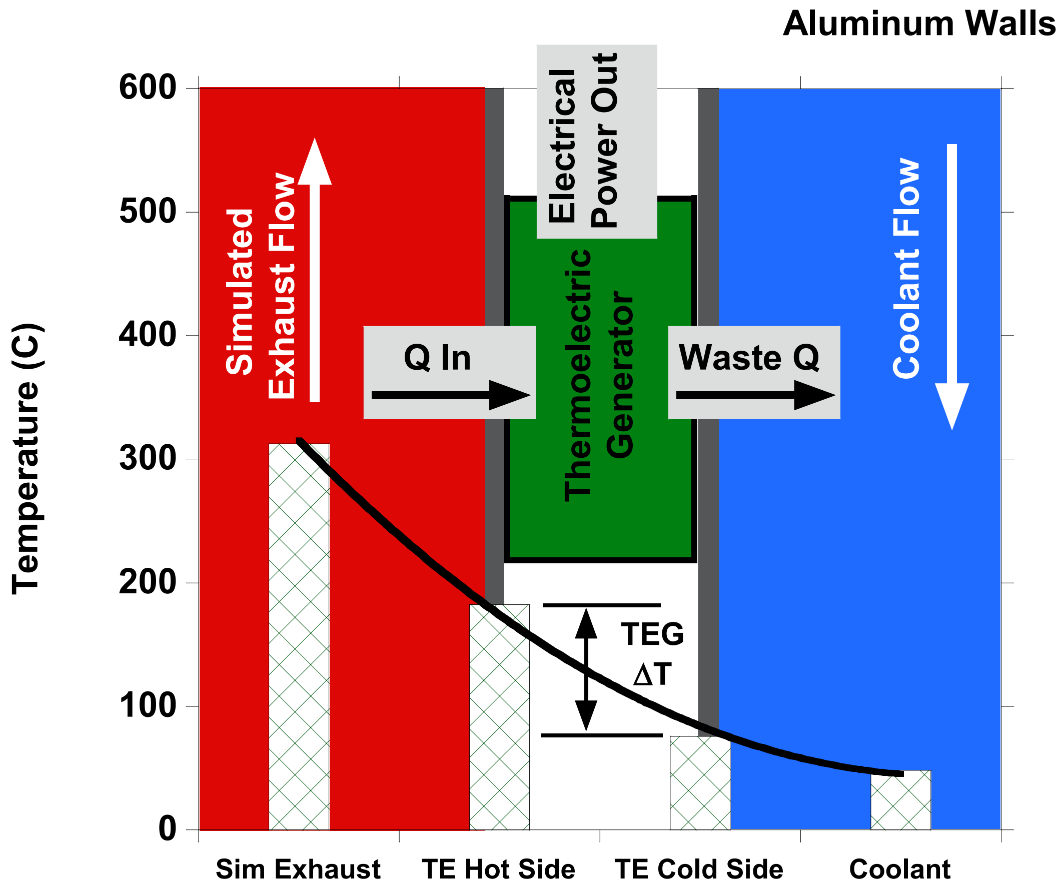
Basic operating characteristics for hollow rectangular duct





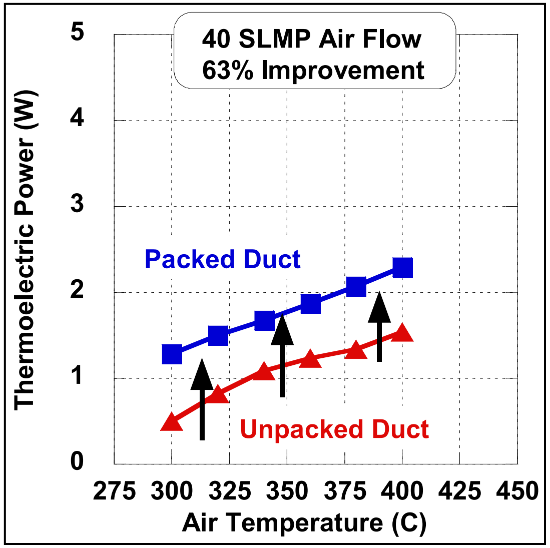
- Hot-side bulk temperature and surface temperature decreases
- Temperature drop from bulk gas temperature to hot-side thermoelectric temperature is very significant
  - > 100 C at most conditions, more than half the total temperature gradient
- Surface temperature gradient dictates thermoelectric power generation

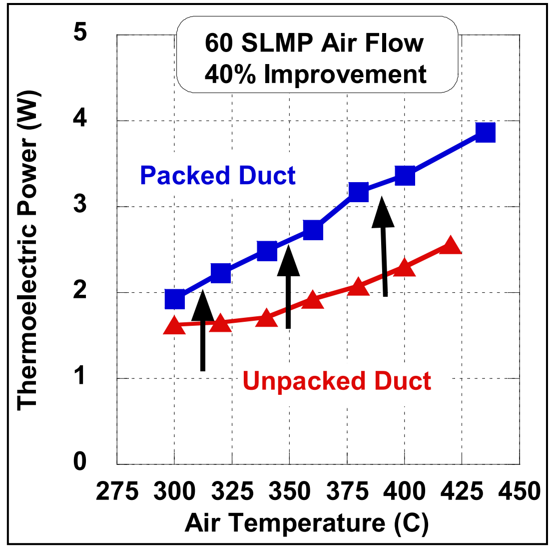
Heat transfer to the thermoelectric is a major impediment to greater exhaust heat recovery

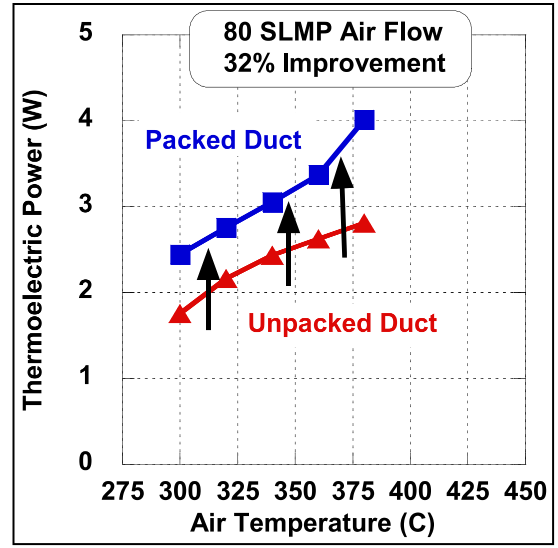


Packed duct increases heat recovery at all flow rates

Largest percent increase in thermoelectric power occurs at lowest flow







- Hypothesis is that the packing material increased heat transfer by increasing conductive heat transfer to walls and reducing boundary layer effects
- Added backpressure is a concern, but packing material filled only 2.5% of duct interior volume
  - No backpressure increase was measured in this experiment
- Other published attempts to increase heat transfer, such as fins and diffusers, are typically more effective at highest flows

Additional year 1 results and conclusions

- Thermoelectric power increased with an increased ΔT across thermoelectric device
  - Increase in hot-side temperature
    - Higher temperature of simulated exhaust
    - Higher simulated exhaust flow rate
    - Packed duct rather than hollow duct
  - Decrease in cold-side temperature
    - Practical constraints for a dedicated cooling system for thermoelectrics
- Maximum system efficiency was low, less than 1%
  - Literature survey shows that this is comparable to thermoelectric system efficiencies during vehicle demonstrations

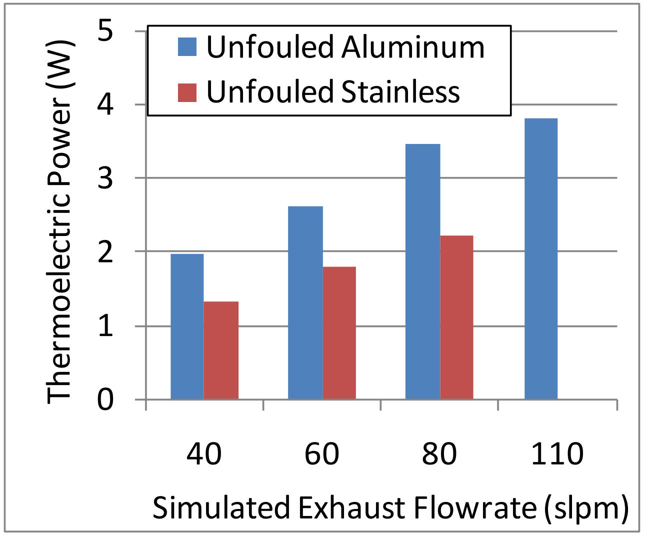
$$\eta_{System} = \frac{P_{Electricity}}{Q_{Exhaust}} = \eta_{Heat\_Exchanger} * \eta_{Thermoelectric}$$

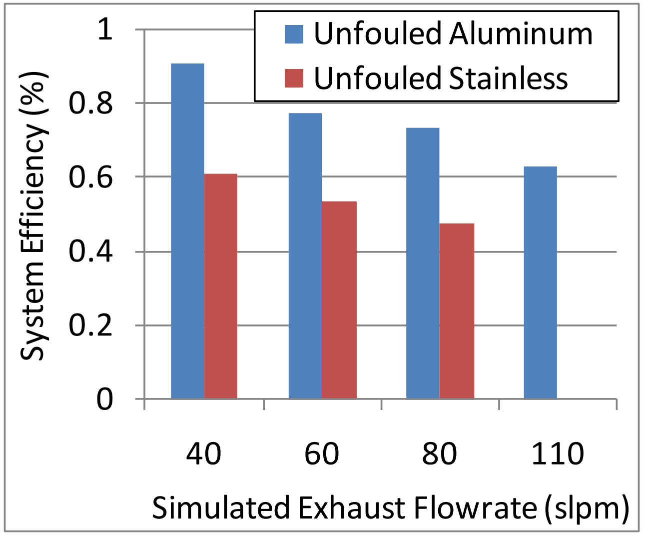
Year 2 study: Investigate the effect of heat exchanger material and heat exchanger fouling on heat transfer, thermoelectric performance

- Use multi-port heat exchanger design
  - Similar to heat exchangers in EGR coolers

- Aluminum and stainless steel heat exchangers
  - Aluminum k ~ 180 W/m-K
  - Stainless k ~ 20 W/m-K
- Experimental approach:
  - Fabricate duplicate aluminum and stainless steel heat exchangers
  - Perform parametric study with un-fouled heat exchangers
  - Expose duplicate heat exchangers to engine exhaust at conditions conducive to thermophoresis to rapidly foul the heat exchanger
  - Repeat parametric study with fouled heat exchangers

Aluminum heat exchanger performance was superior to stainless steel

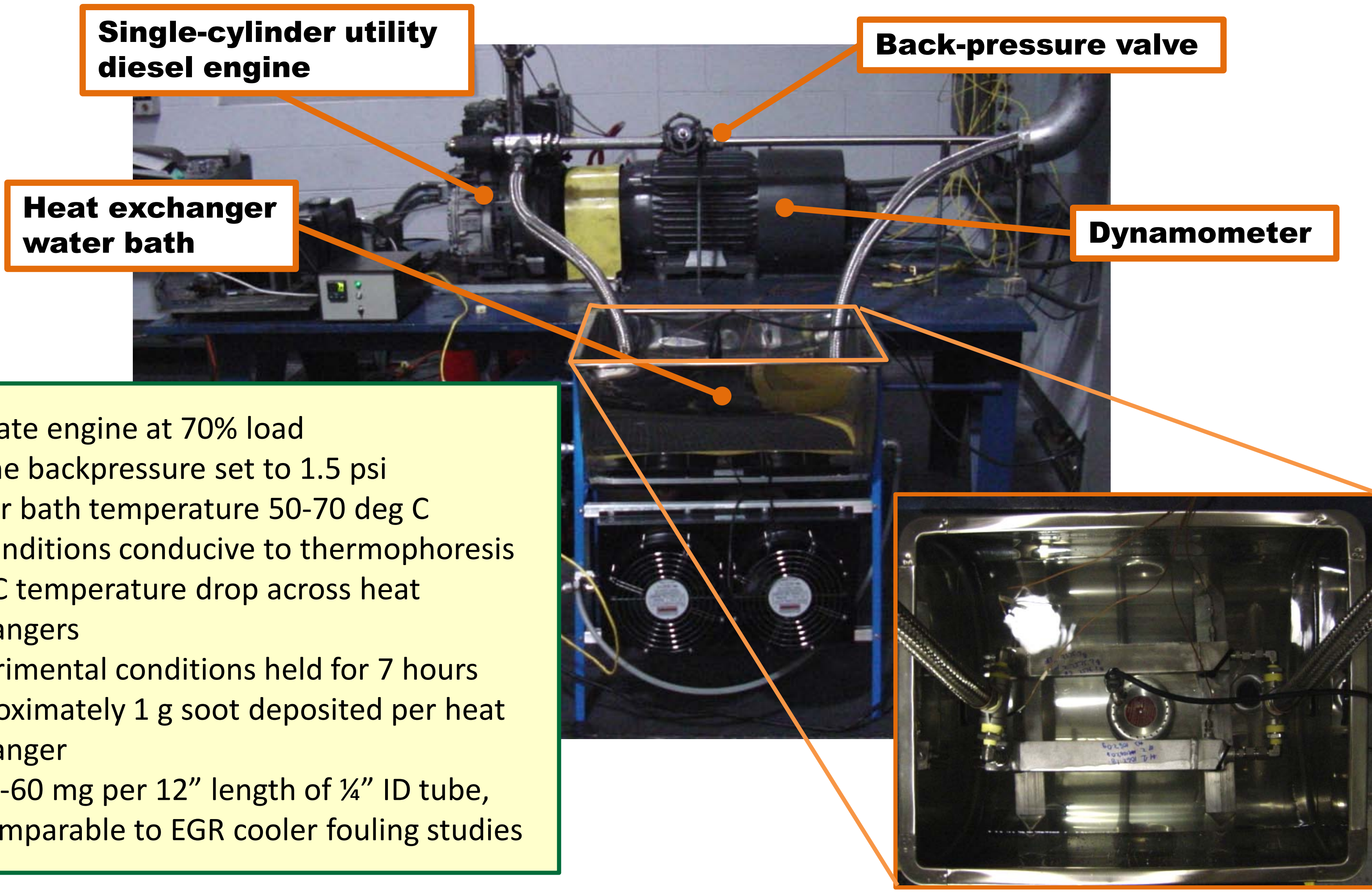




Total heat recovery from five thermoelectric generators in-series.
Simulated exhaust T= 380 deg C, Coolant T = 40 deg C

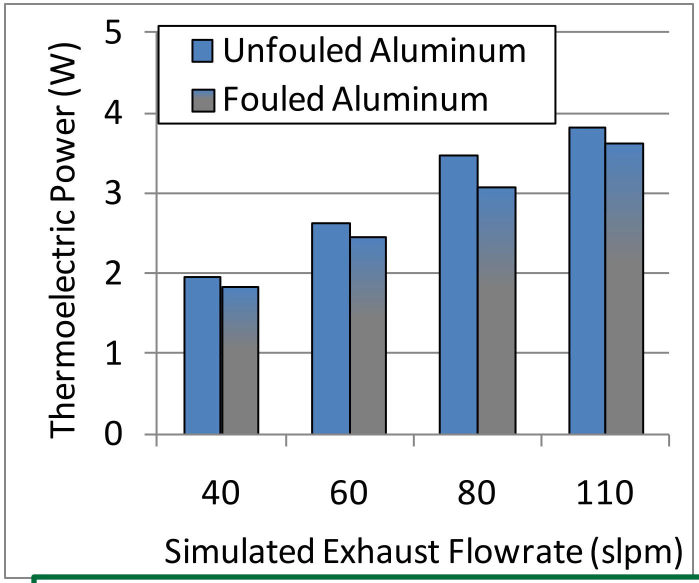
- **Aluminum heat exchanger provides a 40-60% increase in thermoelectric power output compared to stainless steel**
  - **Thermal conductivity of aluminum is approximately 9x higher than stainless steel**
  - **High exhaust temperatures may limit use of aluminum heat exchangers**
- **Although recovered power increases at higher flow rates, system efficiency decreases**
  - **Higher heat flux at the higher flow rate**

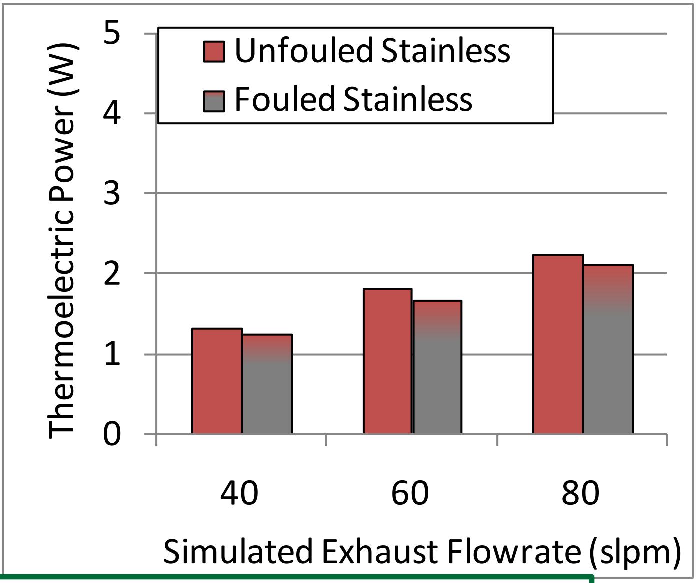
Heat Exchanger Fouling Procedure



- Operate engine at 70% load
- Engine backpressure set to 1.5 psi
- Water bath temperature 50-70 deg C
  - Conditions conducive to thermophoresis
- 130°C temperature drop across heat exchangers
- Experimental conditions held for 7 hours
- Approximately 1 g soot deposited per heat exchanger
  - 50-60 mg per 12” length of ¼” ID tube, comparable to EGR cooler fouling studies

Fouled heat exchangers reduced performance





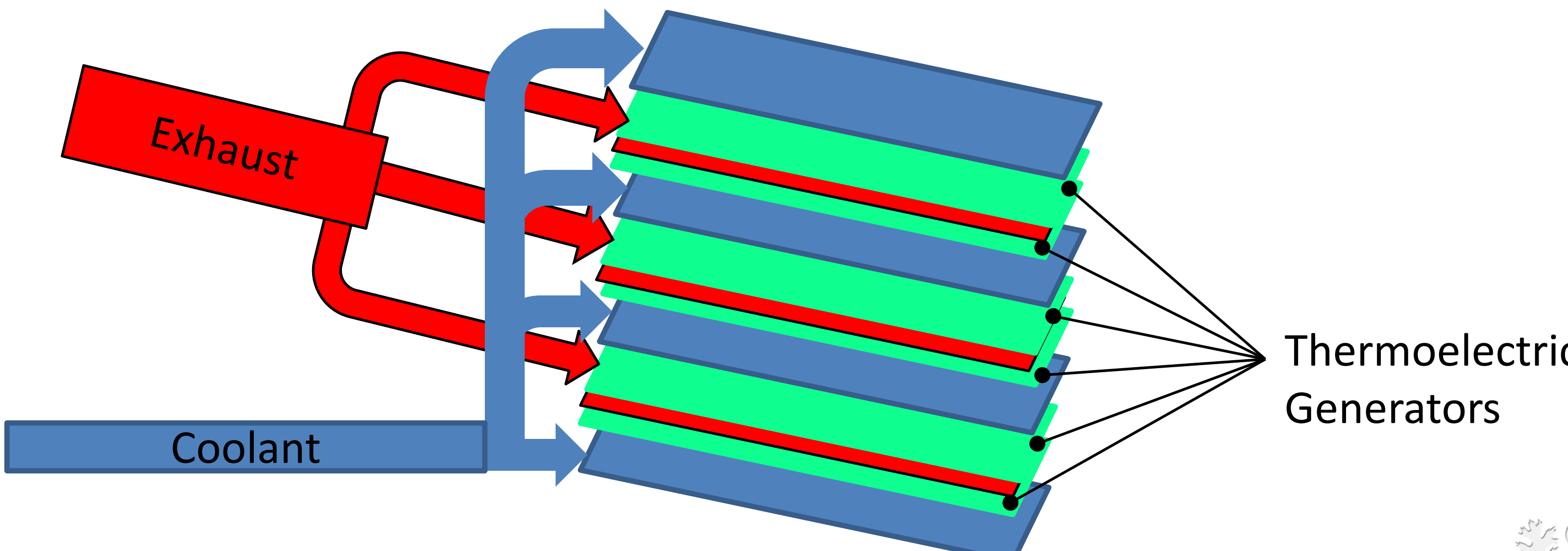
Total heat recovery from five thermoelectric generators in-series.
Simulated exhaust T= 380 deg C, Coolant T = 40 deg C

- **Performance of thermoelectric devices is degraded 5-10% compared to unfouled heat exchanger**
  - **Heat exchanger on material has a much more significant impact on performance than fouled and unfouled duct**
  - **Result seeming contradict EGR cooler fouling, where heat exchanger effectiveness can be reduced by more than a third with similar soot loading**

Why does the heat exchanger material have a larger effect than heat exchanger fouling?

- **Heat exchanger design was not optimal**
  - **EGR coolers typically have thin walls, creating minimal resistance to heat transfer**
  - **Heat exchanger used in this study had much longer characteristic heat transfer length, and created a substantial resistance to heat transfer**

- **Proposed improved heat transfer design is multi-layer flat-plate arrangement with thermoelectric devices sandwiched between heat exchanger layers**
  - **Additional complexity, system weight, and cost**



Conclusions

- Thermoelectrics can recover part of the large amount of waste heat available in the exhaust systems on gasoline and diesel engines, BUT… capture and conversion to useful work can be difficult
  - Exhaust system is sized for full engine load, while the majority of the operating map is spent at part-load conditions
  - Result is that heat exchangers must work well over a wide dynamic range
- Packing heat exchanger with aluminum wool enhanced heat transfer, thermoelectric performance
  - Use of aluminum may not be practical with high temperatures in automotive exhaust systems, but similar performance expected from stainless steel wool
  - Packing density can be low to minimize the exhaust backpressure
- Heat exchanger fouling degrades heat exchanger performance
  - Fouling of heat exchanger surfaces is a real-world challenge for EGR coolers, and is expected to be problematic for all exhaust heat exchanger systems on diesel engines
  - Heat exchanger fouling decreased recovered power by up to 10%
  - With better heat exchanger designs, fouling layer is expected to degrade performance further

Acknowledgements

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