Organic Rankine Cycle for Light Duty Passenger Vehicles

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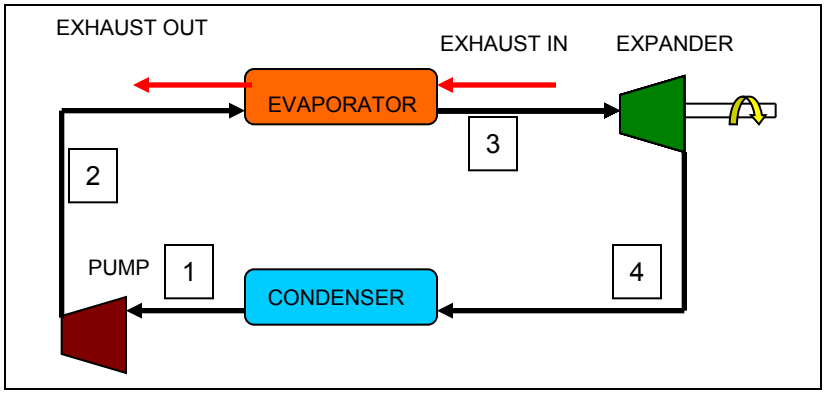
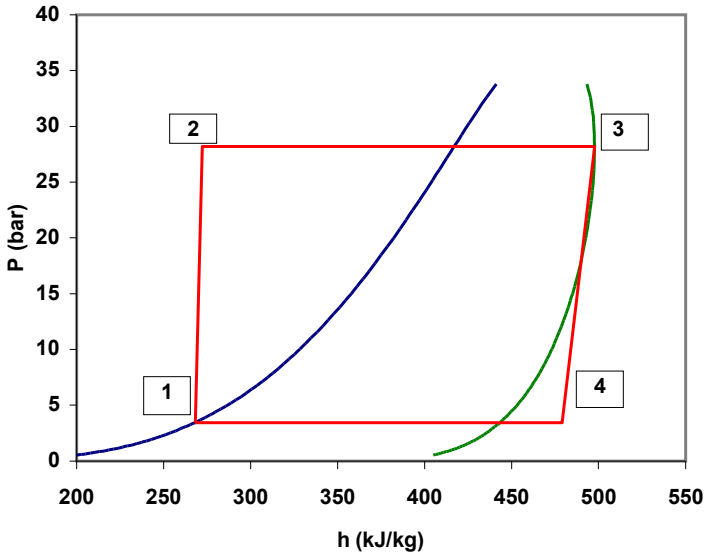
System Configuration





Key Questions

- Can we generate power from waste heat using ORC in a light duty passenger vehicle?
- Is the amount of power generated sufficient to bring about a fuel economy benefit?
- What are the power output characteristics for a conventional and a hybrid vehicle?
- What is the backpressure effect?

Content Overview

- Approach
- Design Sensitivities and Trade-offs
- System Behavior
- Power Output
- Backpressure Effect
- Summary

Approach: Overview

Exhaust enthalpy vs. time (downstream of cat converters)

Model

- Mech. power vs. time
- Elec. power vs. time
- System backpressure

- ORC Operating conditions
- Component size/geometry

Features:

- Fully transient
- Includes effect of fluid and component warm-up
- Includes dependencies on key design parameters for each component
  - Allows Design of Experiment based investigations and optimization

Approach: Working Fluid Selection

- Advantageous properties of organic fluids:
  - Very low (-100 C) freezing point
  - “Dry fluid” - after expansion it stays in superheated region → no need to superheat
  - Low condensation temperature → Coolant heat can be used to preheat the fluid which can increase power output
- Issue with organic fluids:
  - Cooling with ambient air requires large condenser surface area due to small temperature difference.
- R245fa selected for this study:
  - 1,1,1,3,3,-pentafluoropropane; $CF_3CH_2CHF_2$
  - No Ozone impact
  - Low Global Warming Impact
  - Non-flammable
  - Thermodynamic state properties evaluated from NIST database REFPROP V7

Approach: Model Features

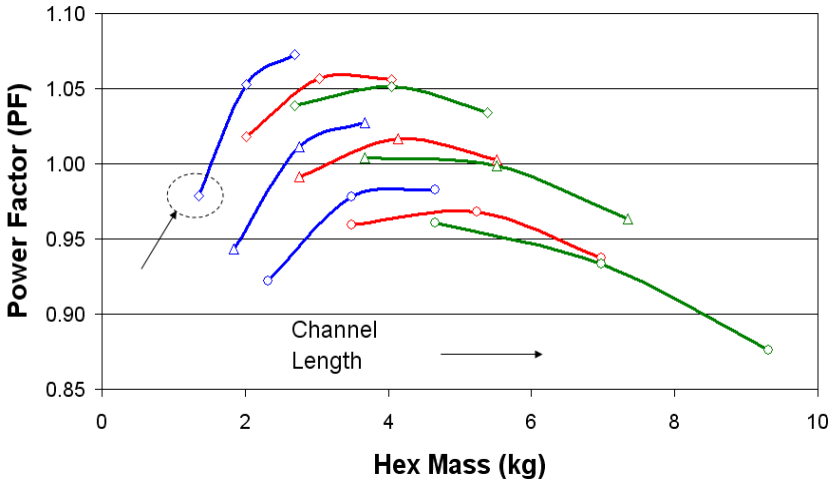
- The evaporator is shell & tube type with exhaust gas passing through the tubes.
- Heat transfer on gas side use familiar Re-Pr correlations
- The evaporator uses Rohsenow nucleate pool boiling correlation.
- The high side and low side pressures are held at a fixed value.
- The mass flow of working fluid varies with the available heat.
- The efficiency of the pump and turbine are assumed to be constant .
- No heat is lost to the surroundings.
- Condenser is modeled as a heat sink.

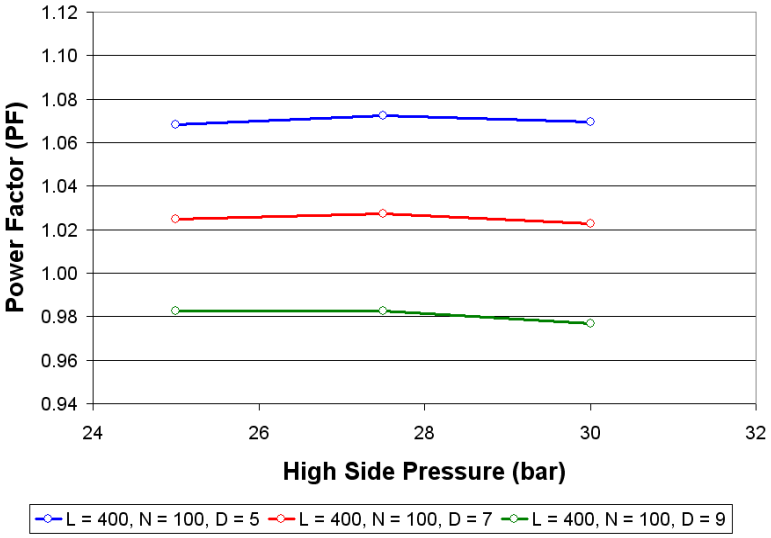
Design Sensitivity Studies

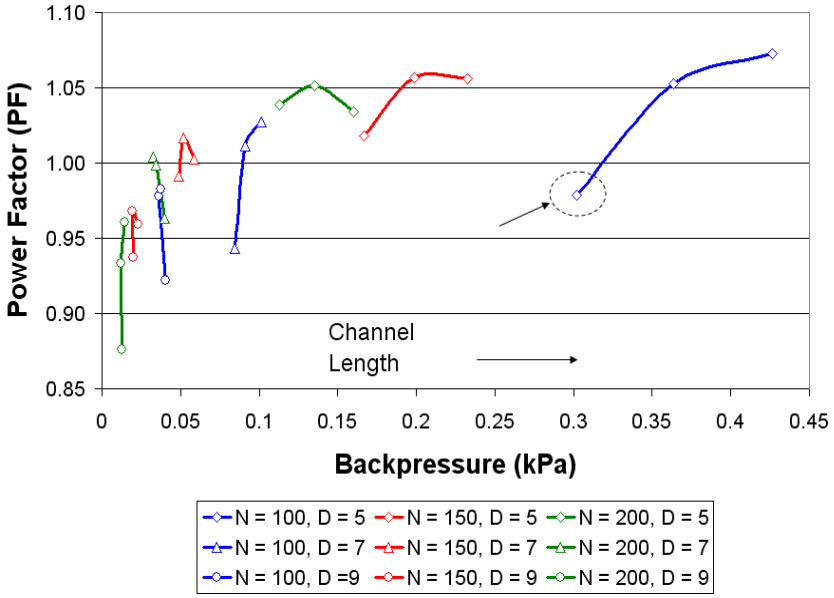
- **Evaporator Design:**
  - Length: 200mm → 400 mm
  - Number of tubes: 100 → 200
  - tube diameter: 5mm → 7 mm
  - volume: 1.125L → 8.0L
- **High Side Pressure:** 25 bar → 30 bar
- **Low Side Pressure:** 3.54 bar
- **Component Efficiencies**
  - Expander: 50%
  - Pump: 50%
  - Heat exchanger: 50%
  - Generator: 80%

DOE Results

2009 Escape Highway Drive Cycle







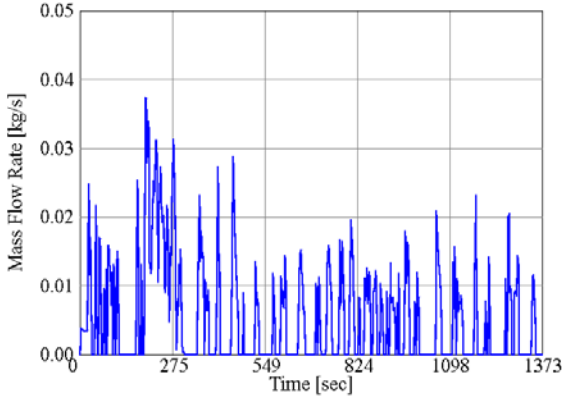
$$Power\ \ Factor = \frac{Power\ Generated}{Vehicle\ Accessory\ Load}$$

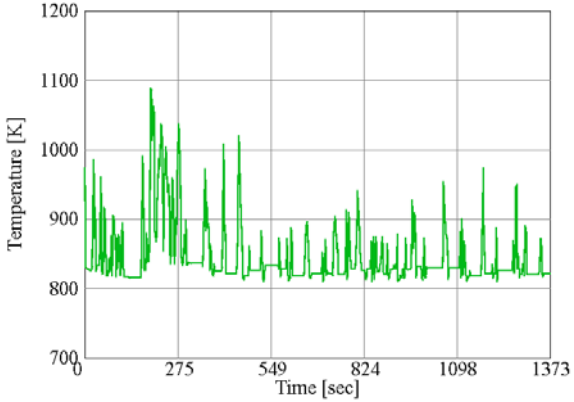
Critical Trade-Offs

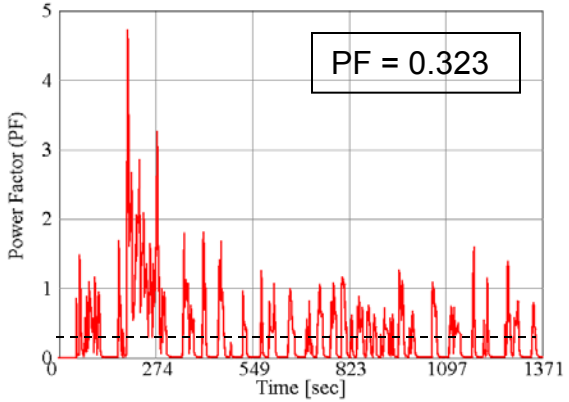
- Increasing evaporator size:
  → Increased power output
  → Large thermal mass → poor drive cycle transient performance
- Small tube diameter/tube number:
  → Smaller package
  → High backpressure
- Increasing peak working pressure:
  → Increased power output
  → Increased expander cost
- Designs selected for detailed study:
  – L = 200mm, D = 5mm, N = 100
  – 25 bar peak pressure

System Behaviors (HEV)

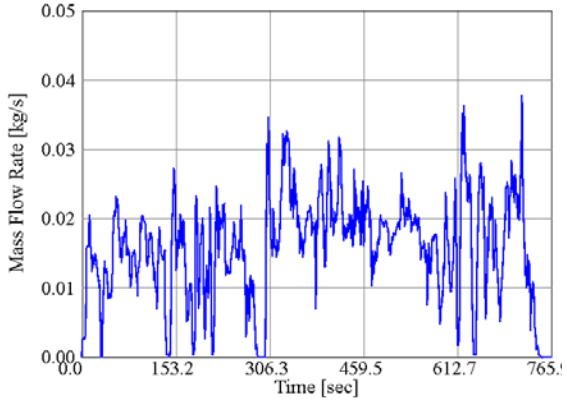
City drive cycle

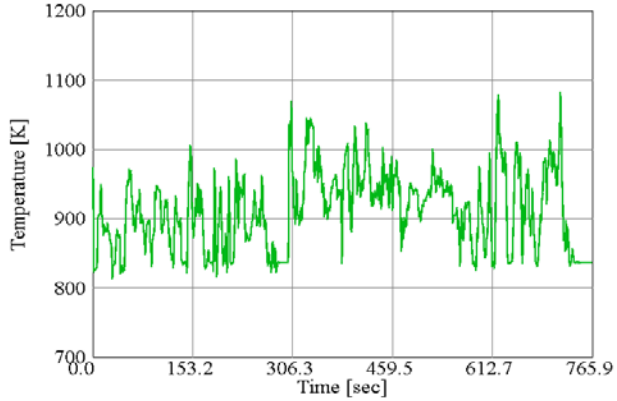


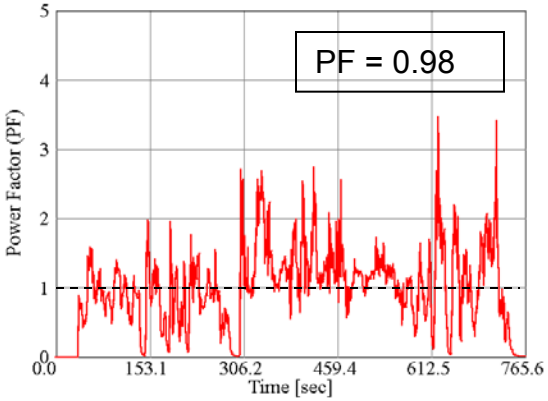




Highway drive cycle

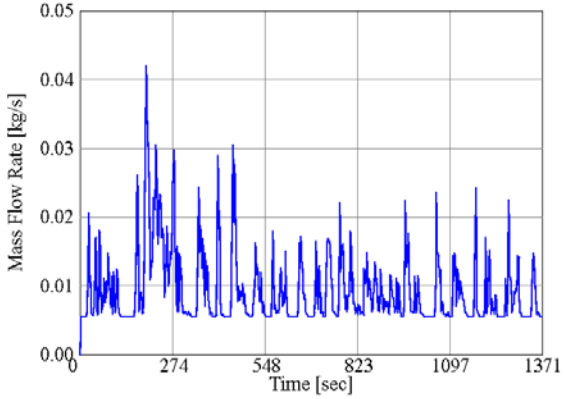


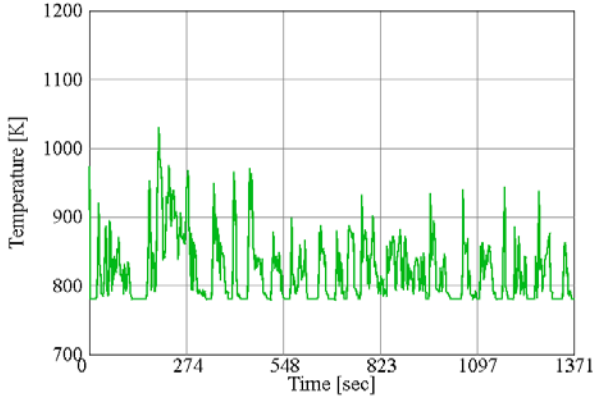


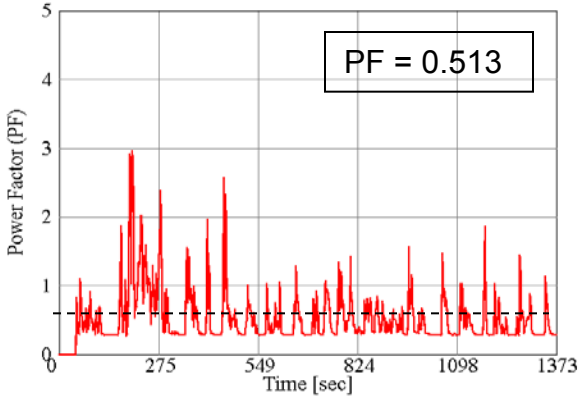


System Behaviors (Conventional)

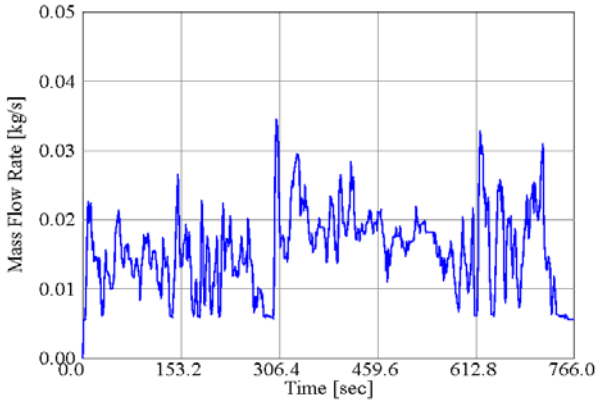
Conventional City drive cycle

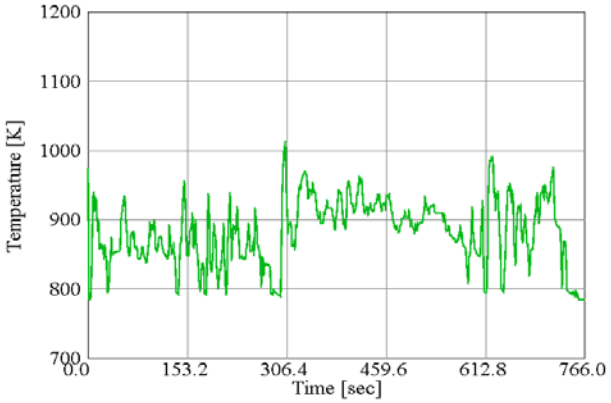


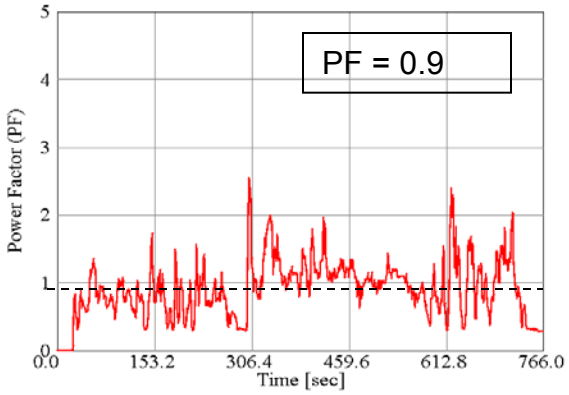




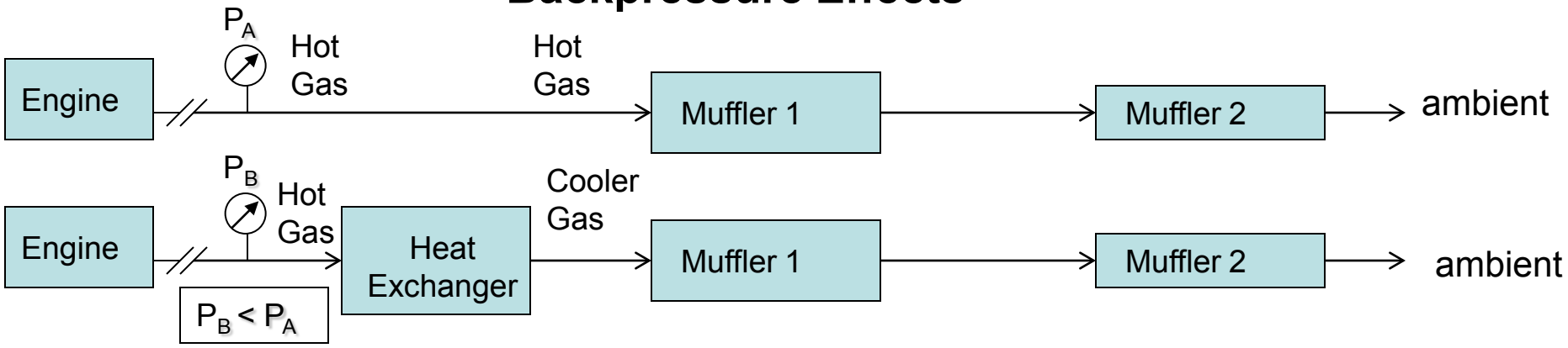
Conventional Highway drive cycle

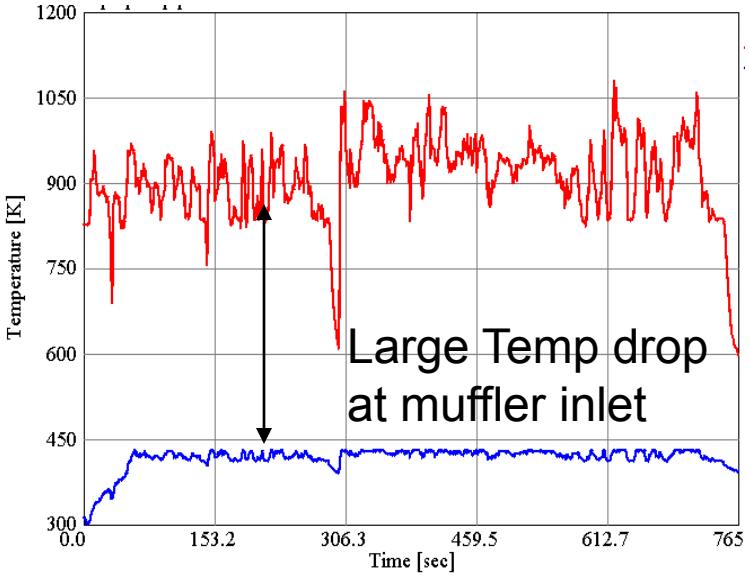


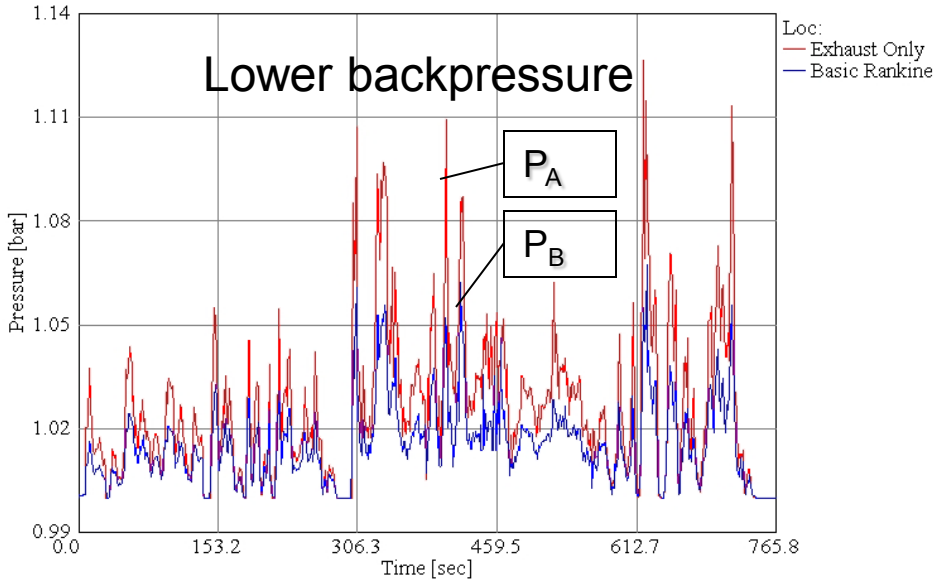




Backpressure Effects

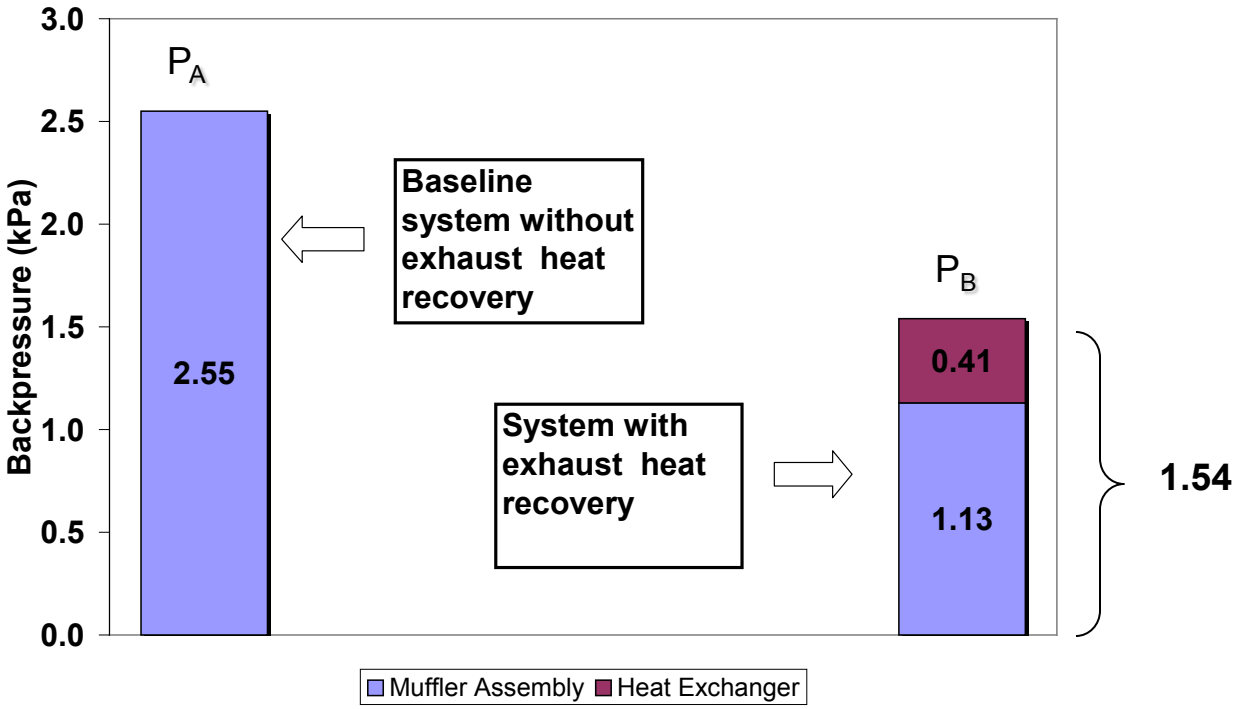






- For the above case, engine back pressure actually decreases due to lower temperature entering the muffler system
- The back pressure effect depends on the heat exchanger design, e.g. if the heat exchanger is too restrictive to flow then backpressure will increase

Cycle Avg. Backpressure



Whether backpressure would go up , go down, or stay the same depends on the heat exchanger design

Summary

- Organic Rankine Cycle using the exhaust waste heat in a light duty passenger vehicle can generate enough electricity to partially offset the accessory load.
- The amount generated varies depending on the type of vehicle, drive cycle, and system size.
- Under EPA highway drive cycle, the system comes close to meeting the electric accessory load demand of the vehicle.
- The output during EPA city cycle is less than the accessory load demand.
- HEV output in city driving is much lower compared to a conventional vehicle due to lower exhaust energy caused by frequent engine shut down events.
- HEV highway output is slightly higher than a conventional vehicle due to higher engine work (higher exhaust energy) needed to propel a heavier vehicle.
- Due to excessive cooling of the exhaust gas in the evaporator, the net backpressure can be actually lower with a well designed ORC system.