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Methods of Increasing Net Work Output of Organic Rankine Cycles for Low-Grade Waste-Heat Recovery

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Paper 2190

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Outline

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- Modeling Effort
- Baseline ORC
- ORC with Two-Phase Flash Expansion
- ORC with Zeotropic Working Fluid Mixtures
- Side-by-Side Comparison
- Future Work
- Conclusion

Introduction

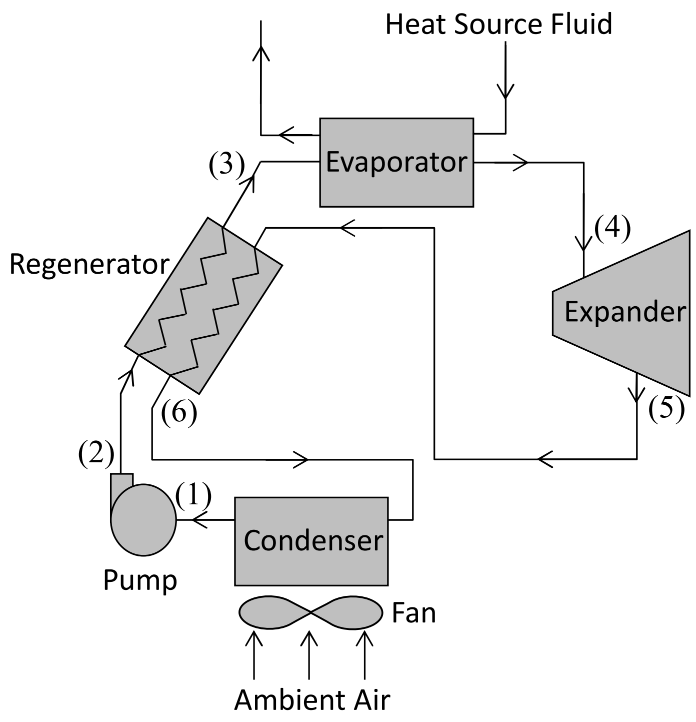
If the input is waste heat, should we maximize thermal efficiency or net work?

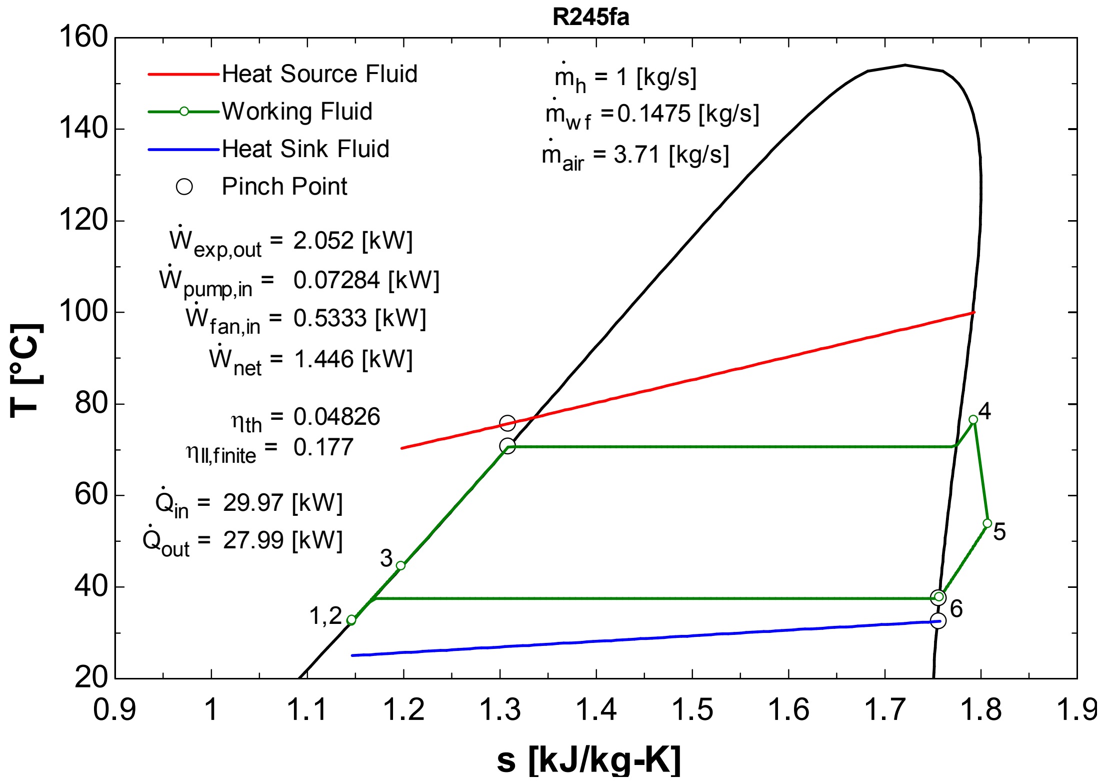
- Should maximize $\dot{W}_{net}$
  - Better to utilize all available heat
  - For a sensible heat source,

$$\max(\eta_{th}) \nRightarrow \max(\dot{W}_{net})$$

Introduction

State points on T-s diagrams correspond to the schematic. Baseline cycle shown.





Modeling Effort

This is a preliminary evaluation of the thermodynamic *potential* of different ORC configurations.

Each model output should represent a "well-designed" system.

$$\eta_{pump} = 0.60,\ \eta_{expander} = 0.75,\ \Delta T_{pinch} = 5\ \mathrm{K}$$

These assumptions say nothing about the cost or difficulty required to achieve them.

Modeling Effort

Global Modeling Assumptions

- One dimensional steady flow
- Steady state
- Negligible pressure drops
- No heat losses
- Source and sink fluids have properties of air at 100 kPa
- Sink temperature of 25 °C

Modeling Effort

Normalized Performance Metric for Finite Capacity Source Fluid

$$\eta_{II} = \frac{\dot{E}_{recovered}}{\dot{E}_{supplied}} = \frac{\dot{W}_{net}}{\dot{m}_h \int_o^{in} \left(1 - \frac{T_o}{T}\right) \delta q}$$

$$\eta_{II,finite} = \frac{\dot{W}_{net}}{\dot{m}_h \left[\int_o^{in} \delta q - T_o \int_o^{in} \frac{\delta q}{T} \right]} = \frac{\dot{W}_{net}}{\dot{m}_h \left[\left(h_{in} - h_o\right) - T_o \left(s_{in} - s_o\right) \right]}$$

Baseline ORC

Design Constraints

Description	Value
Evaporator outlet superheat	≥ 5 K
Expander discharge vapor quality	≥ 0.95

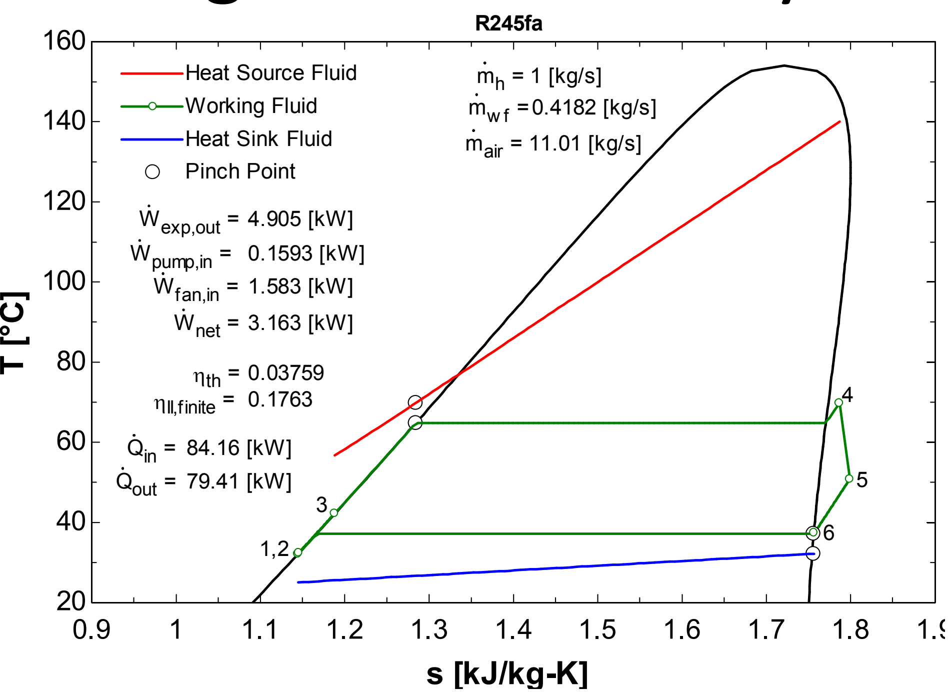
Design Variables

- Low-side pressure
- High-side pressure
- Evaporator outlet superheat

Baseline ORC

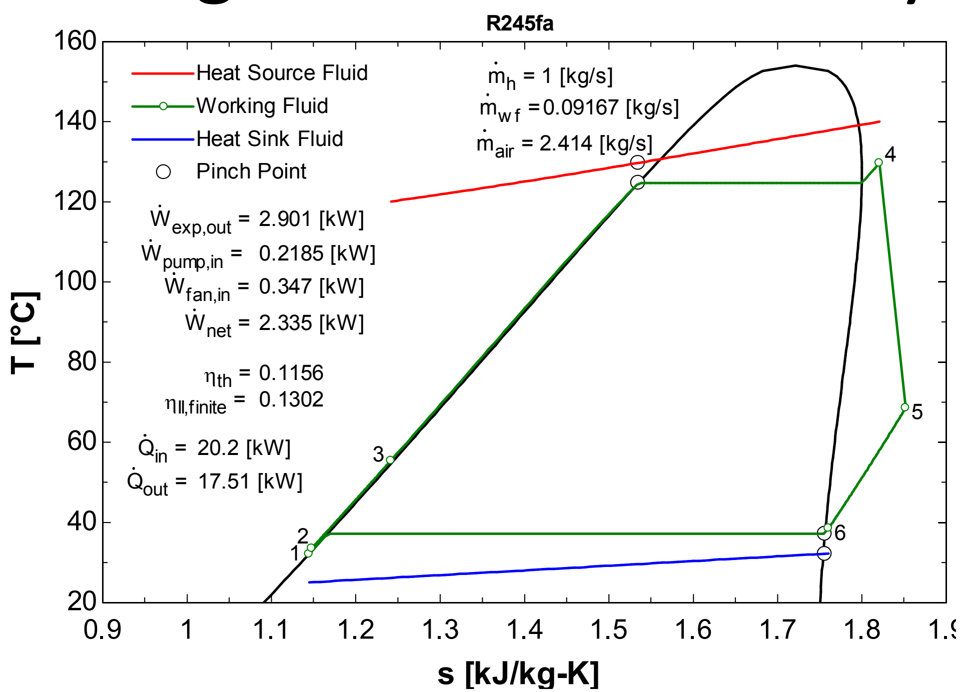
Pinch point location affects cycle net power

High Heat Recovery



Low Thermal Efficiency

High Thermal Efficiency

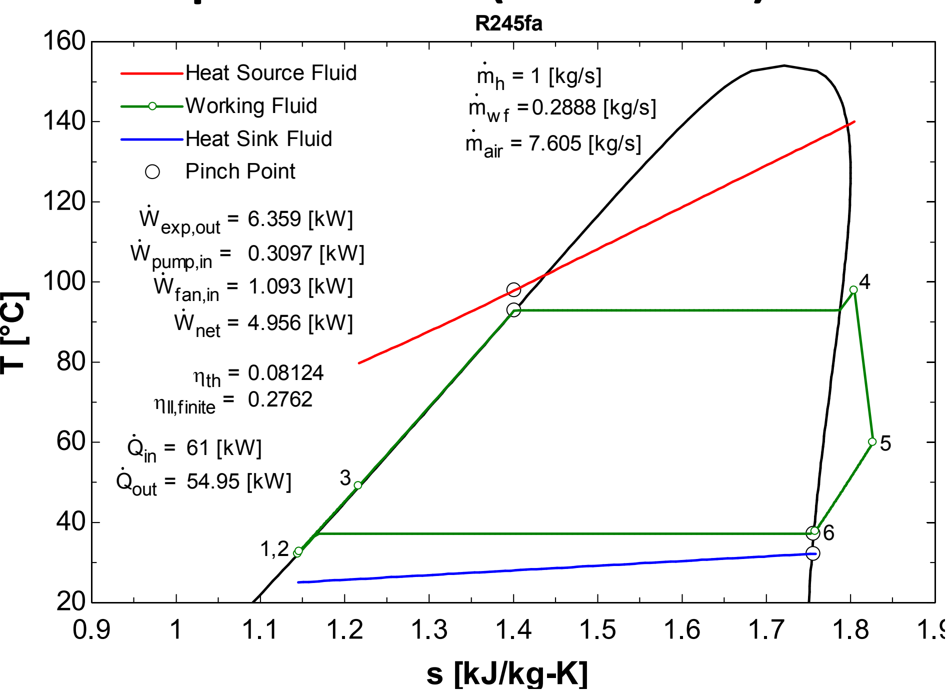


Low Heat Recovery

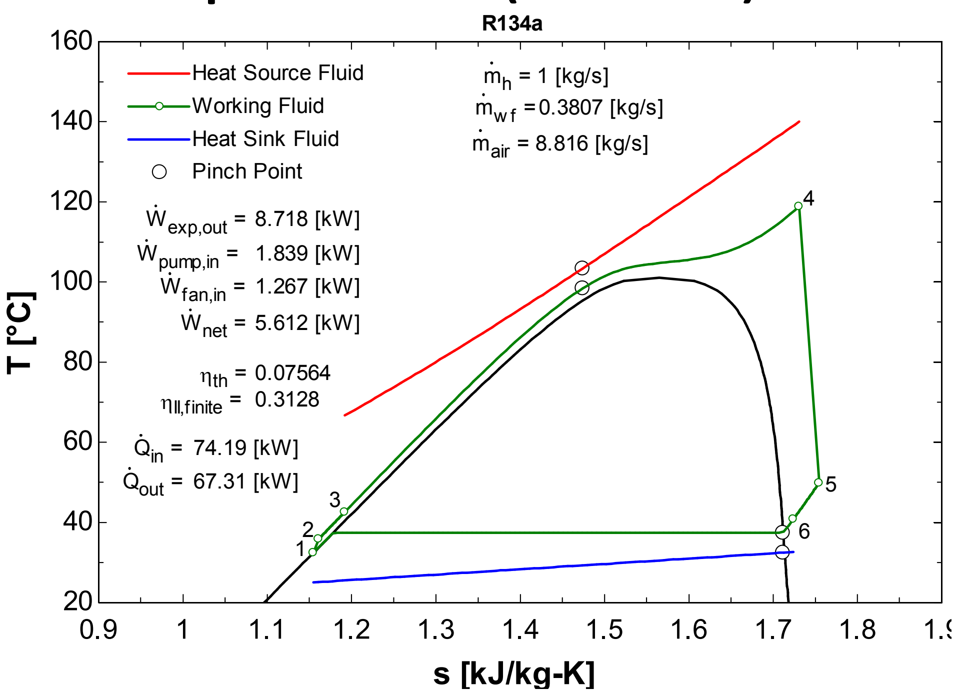
Baseline ORC

The optimum cycle balances heat recovery and thermal efficiency.

Optimum (R245fa)

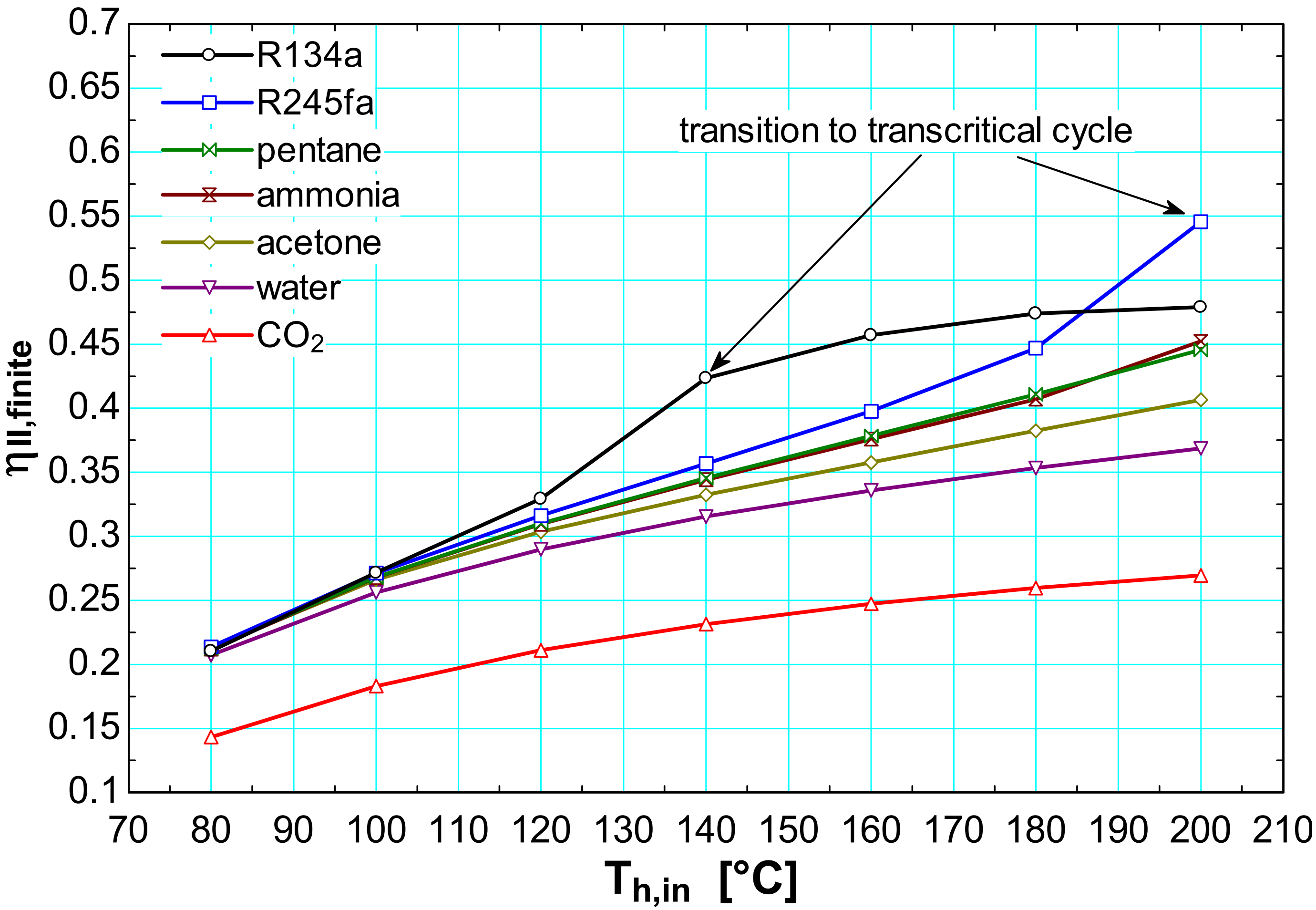


Optimum (R134a)



Baseline ORC

Maximum Second Law Efficiency



Condenser fan power neglected

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ORC with Flash Expansion

We arrive here by removing the baseline ORC constraints:

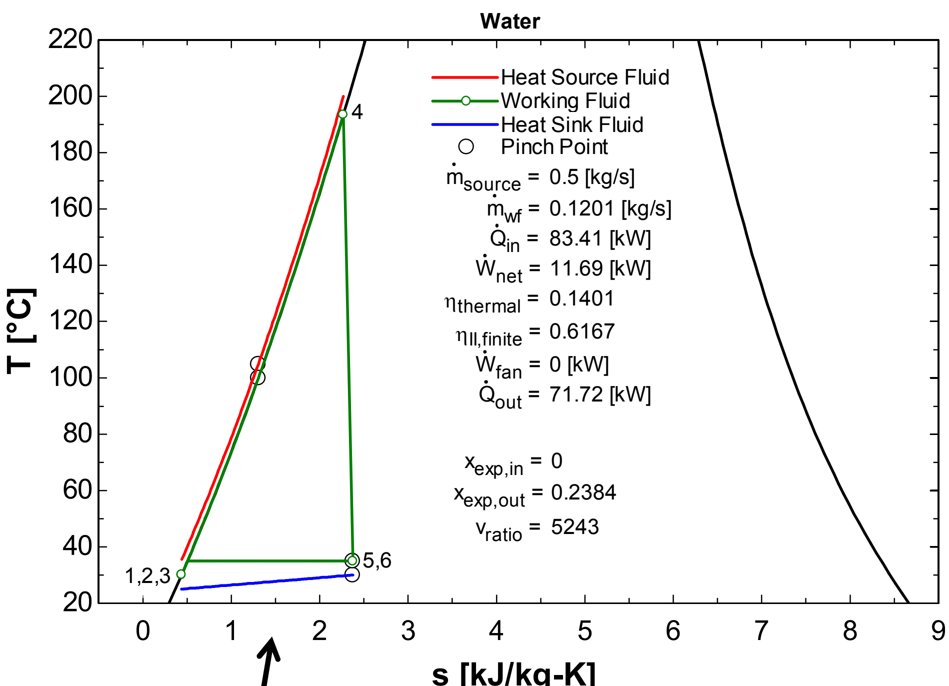
1. ~~Superheat at expander inlet ≥ 5 K~~
2. ~~Expander exhaust quality ≥ 0.95~~

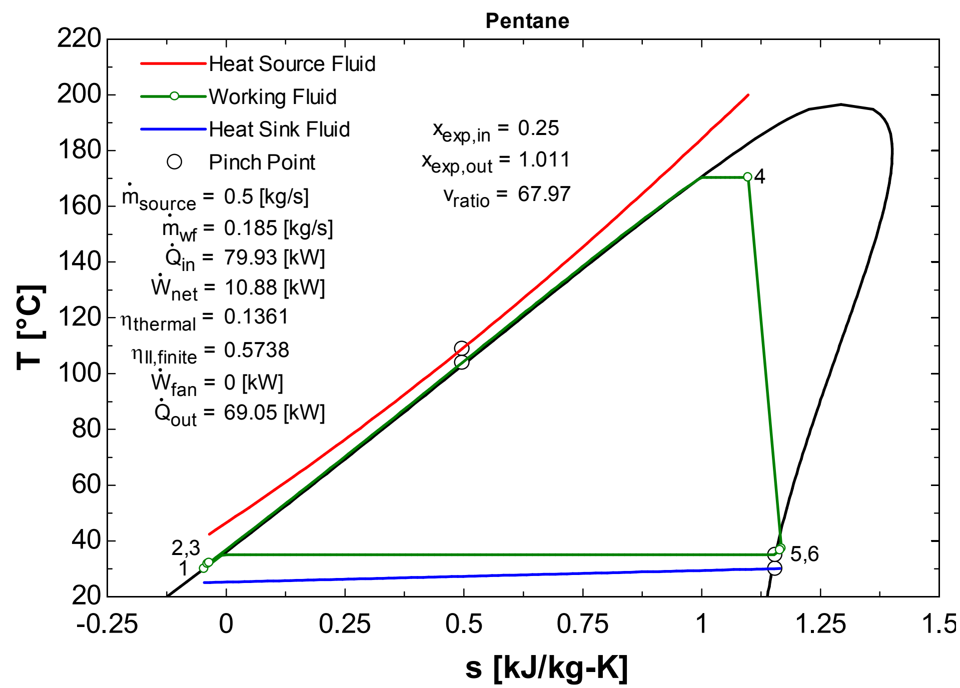
New Design Variables

- Low-side pressure
- High-side pressure
- Evaporator exit state

ORC with Flash Expansion

The expander exit state can be wet or dry, depending on the working fluid and source temperature.



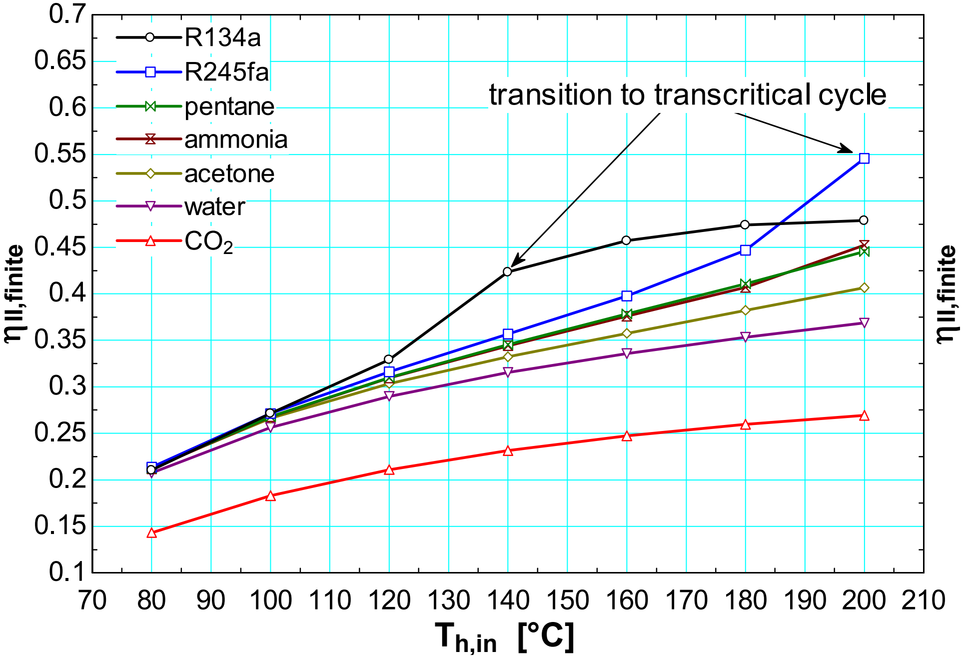


A true trilateral flash cycle (TFC)

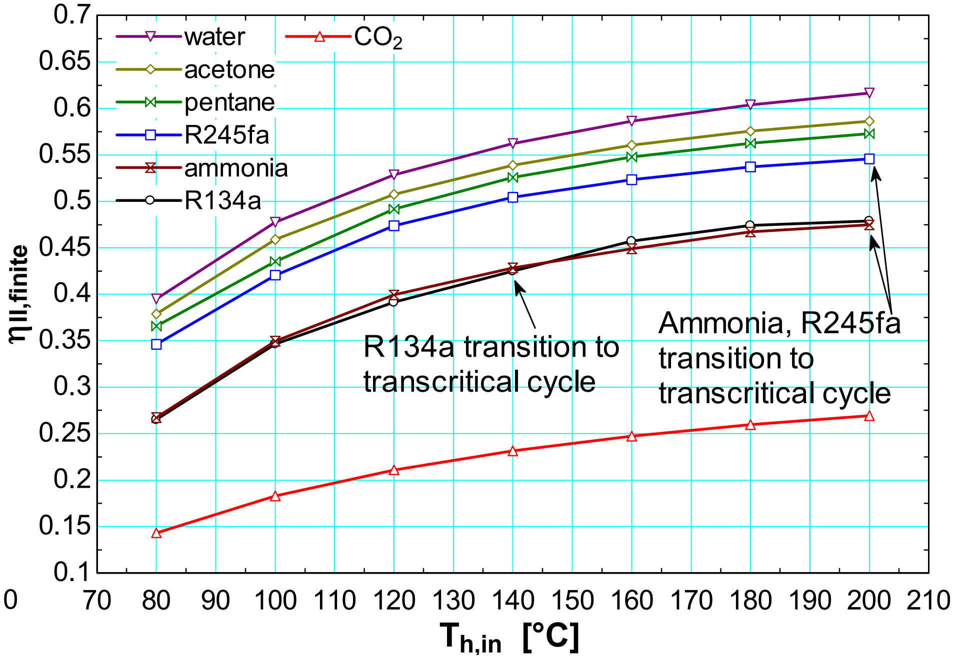
ORC with Flash Expansion

The new design variables change efficiency and working fluid hierarchy dramatically.

Baseline ORC



Unconstrained ORC



ORC with Zeotropic Mixtures (ZRC)

ZRC (zeotropic mixture Rankine cycle)

Design constraints are same as baseline ORC

Description	**Value**
Evaporator outlet superheat	≥ 5 K
Expander discharge vapor quality	≥ 0.95

Design Variables

– Low-side pressure
– High-side pressure
– Evaporator outlet superheat
– Concentration of more volatile component of mixture

ORC with Zeotropic Mixtures (ZRC)

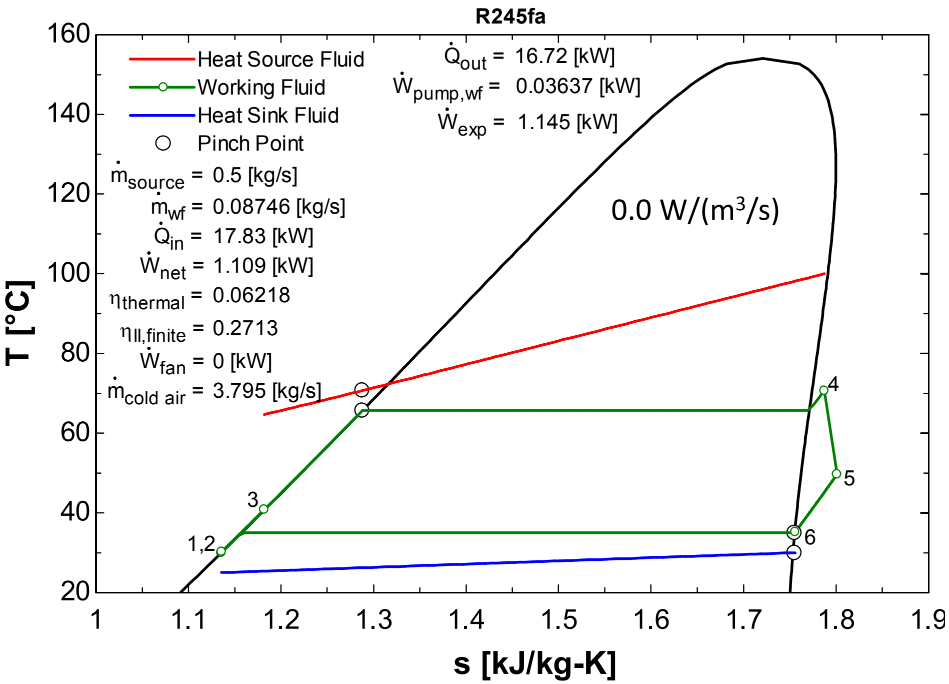
Binary Mixtures Studied

Mixture	Max Low-Side Temperature Glide [K]	Mixing Parameters Available or Estimated in Refprop 9.0
Neopentane-Pentane	6.84	Estimated
Propane-Isobutane	6.89	Available
R245fa-Pentane	7.68	Estimated
Pentane-Hexane	8.25	Available
R227ea-R245fa	9.04	Estimated
R152a-R245fa	12.1	Estimated
R134a-R245fa	14.5	Estimated
Propane-R245fa	32.0	Estimated
Ammonia-Water	97.3	Available
CO_2-Acetone	120	Available

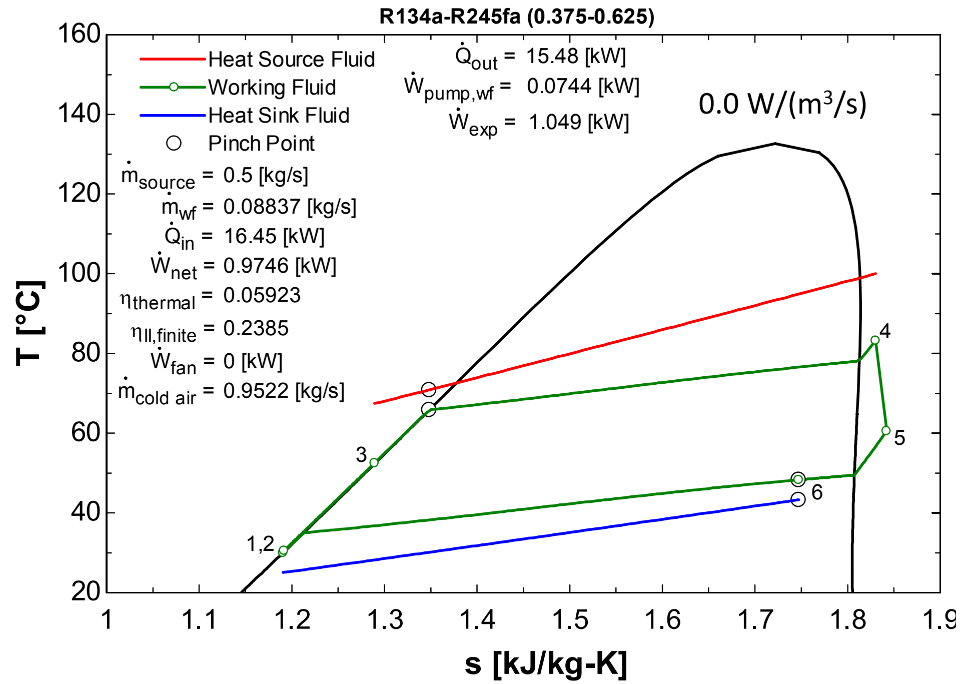
ORC with Zeotropic Mixtures (ZRC)

The ZRC shows no benefit if cooling is free.

Baseline ORC



ZRC



ORC with Zeotropic Mixtures (ZRC)

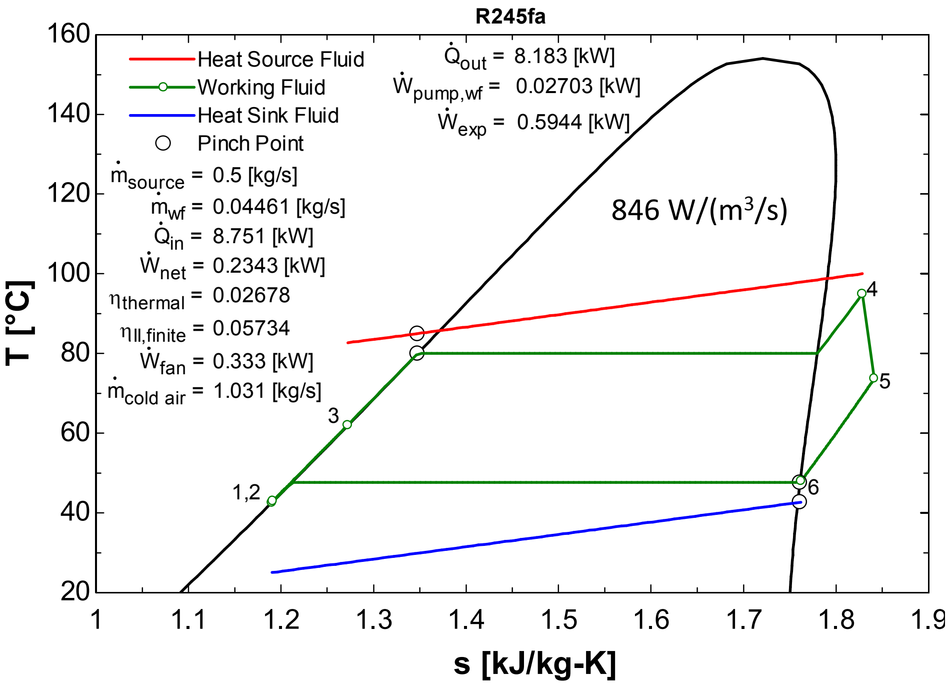
Four air-side fan power requirements used

$\Delta P_{fan,cond}$ [Pa]	η_{fan}	Volume-Specific Fan Power in W/(m^3/s) (W/(ft^3/min)) of air	Comment
0	0.50	0.0 (0.000)	Fan power neglected
50	0.50	100 (0.047)	Lowest value from Yang *et al.* (2007)
84	0.50	168 (0.079)	Equivalent to $\Delta P_{fan,cond}$ =50 Pa and η_{fan} =0.30
423	0.50	846 (0.400)	A standard value for a fully ducted HVAC system

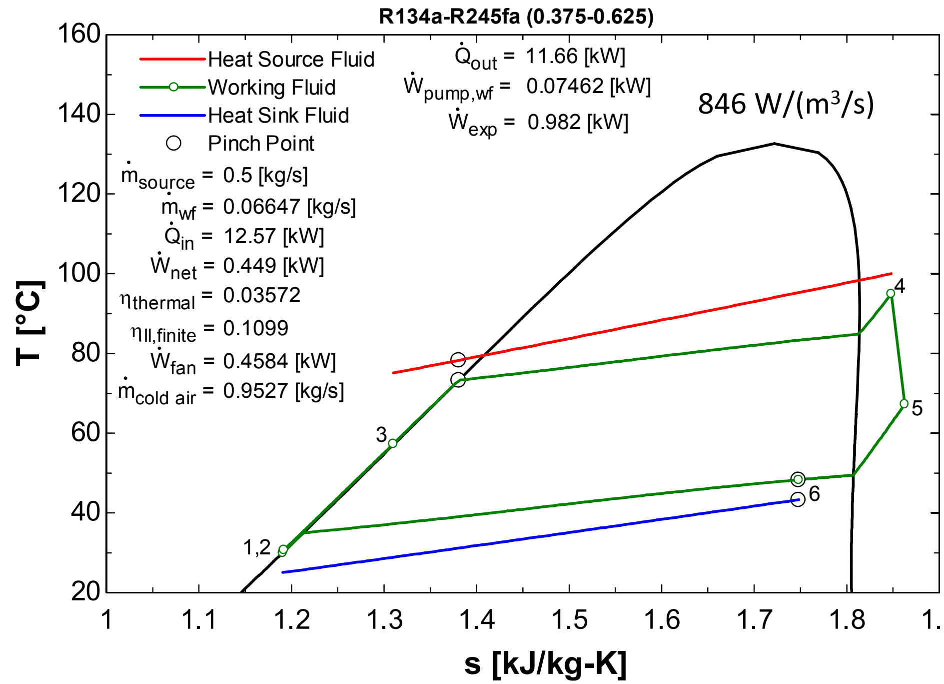
ORC with Zeotropic Mixtures (ZRC)

The ZRC shows a large benefit when cooling is costly ($846\ W/(m^3/s)$).

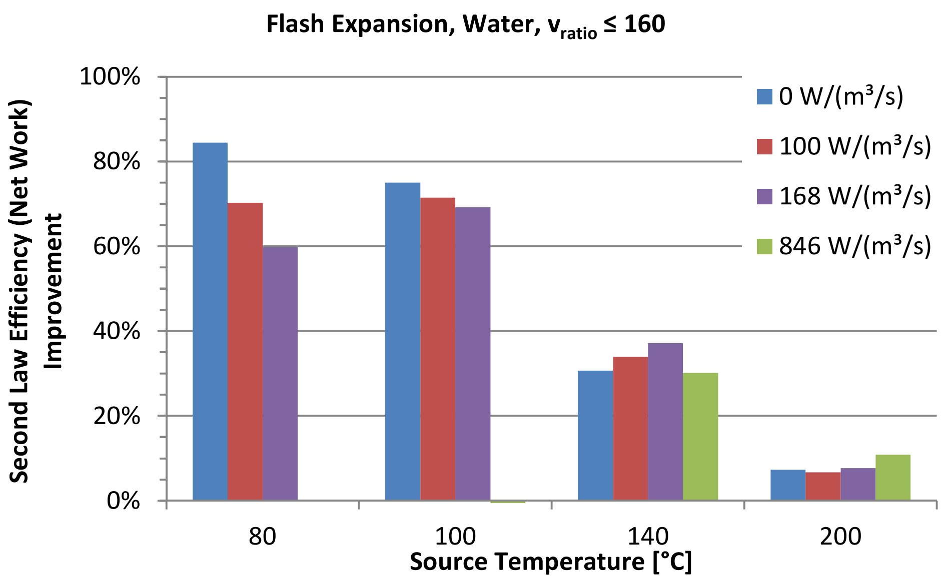
Baseline ORC

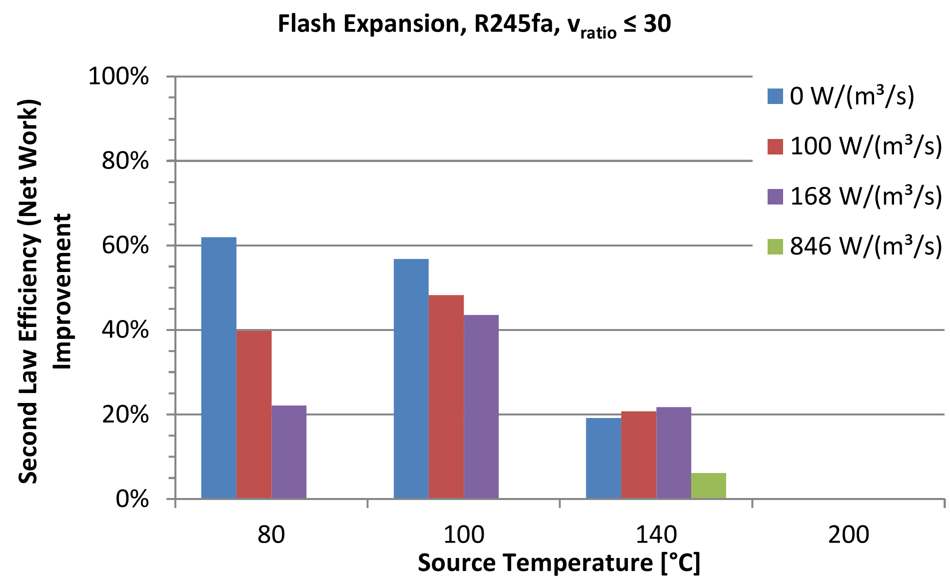


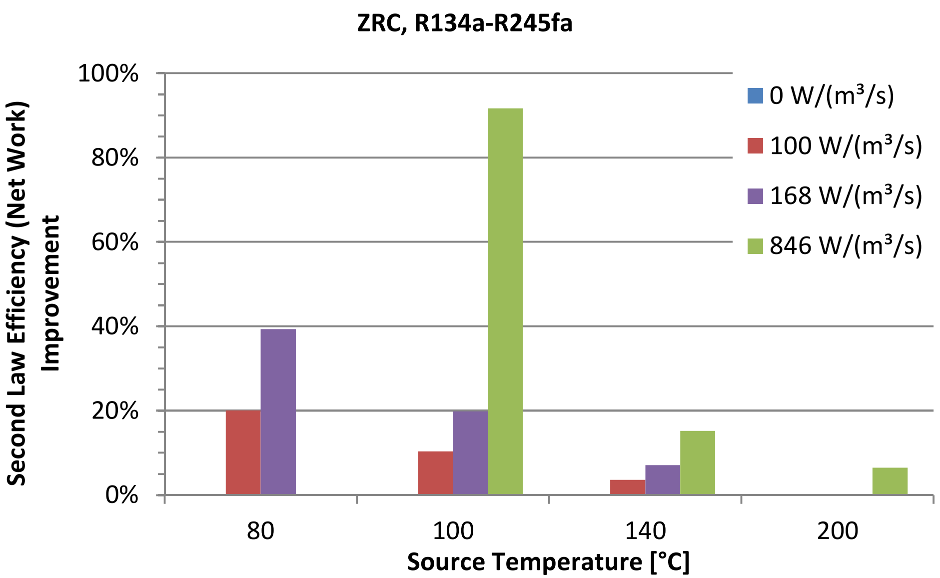
ZRC

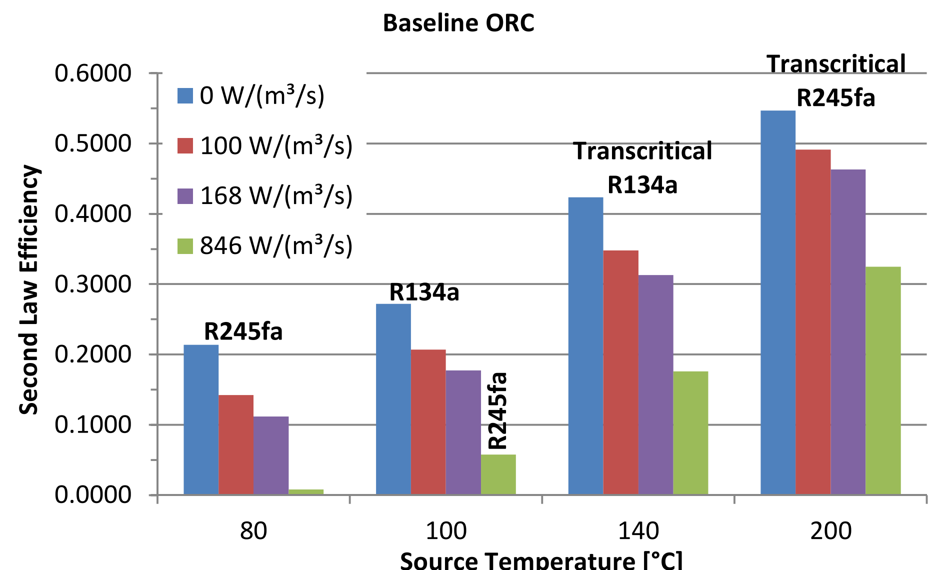


Side-by-side Comparison









Future Work

Propose to experimentally investigate baseline ORC and ZRC with R134a and R245fa

- No major modifications to test stand

Experimental ZRC data using R134a-R245fa

Detailed steady-state ORC and ZRC system models with system charge as input

Conclusion

- Two methods to increase net power production of ORCs from waste-heat sources
  - ORC with two-phase flash expansion
  - ORC with zeotropic working fluid mixtures
- Systems were modeled assuming well-designed components
  - Constant pump and expander isentropic efficiency
  - Constant heat exchanger pinch point temperature difference

Conclusion

ORC with flash expansion offers most improvement

- 84% over baseline at 80 °C (water, 0.0 $W/(m^3/s)$)
- most significant practical challenge is probably in the expander design

ZRC only offers benefit if condenser fan power is not negligible.

- 39% over baseline at 80 °C (R134a-R245fa, 168 $W/(m^3/s)$)
- could utilize existing expander designs

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END