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Performance Analyses of Supercritical ORCs with Large Variations of the Thermophysical Properties in the Pseudocritical Region

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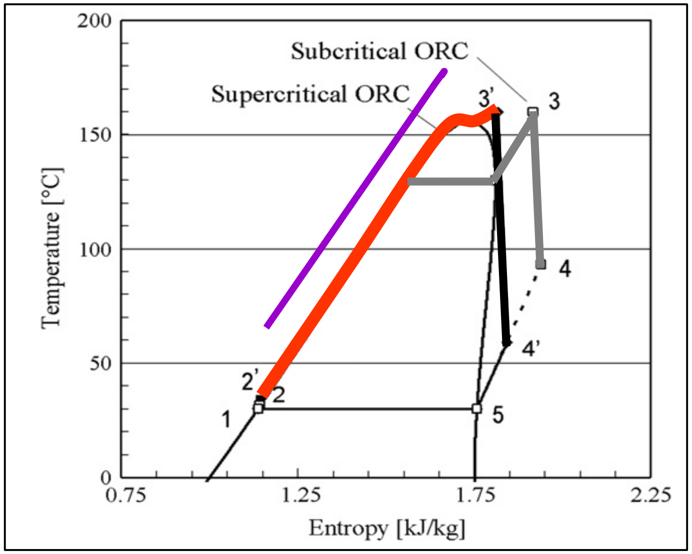
Background

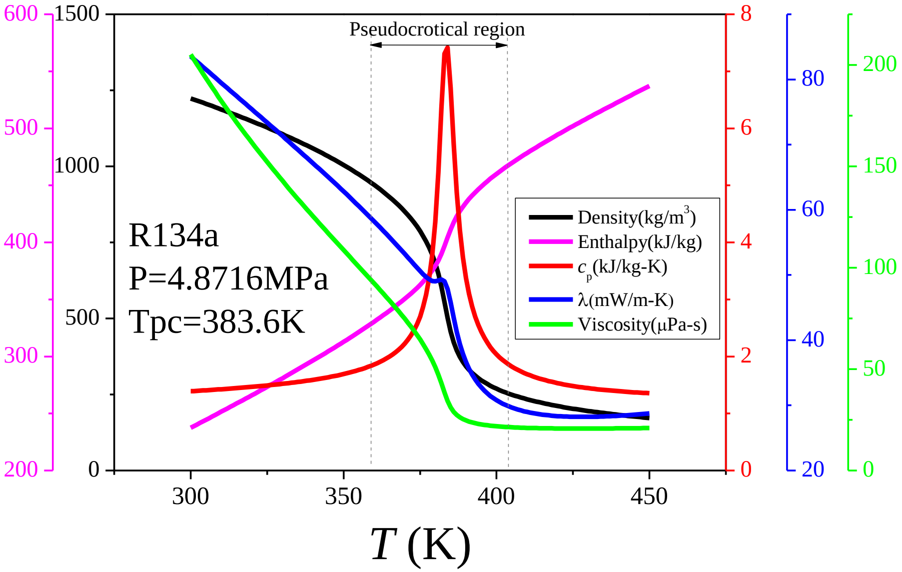
- **Supercritical ORCs**

  High thermal efficiency, exergy efficiency, work output

- **Heat transfer at supercritical pressure**
  - The thermophysical properties have large variations
  - Variations influence the system performance

Key issue

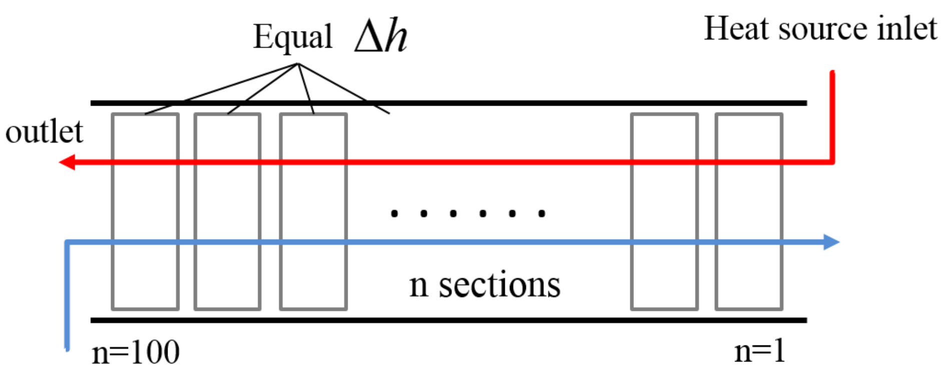


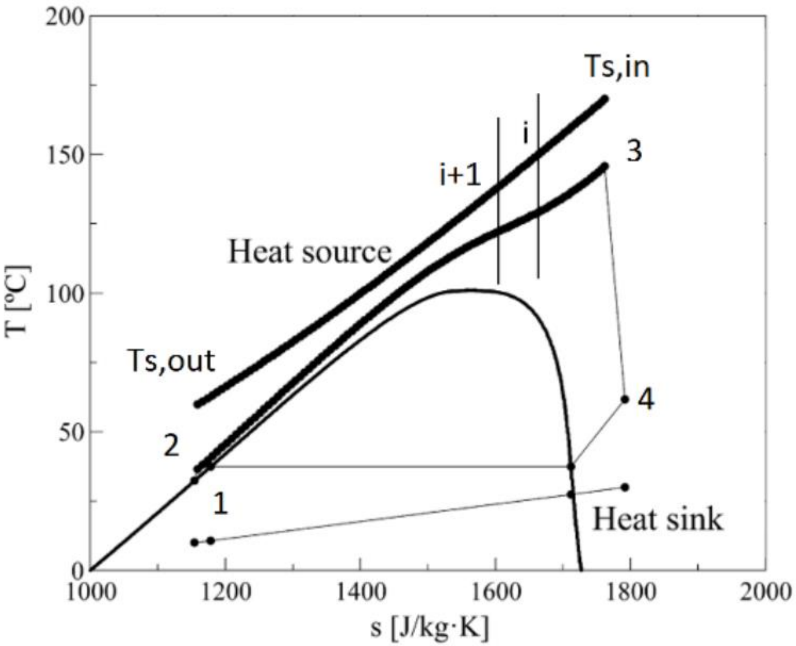


System Modeling

- Basic supercritical ORC cycle
- Vapor generator model
  - A discretized model: 100 sections, equal enthalpy difference Δh
  - Jackson Correlation

$$Nu = 0.0183 \mathrm{Re_b}^{0.82} \mathrm{Pr_b}^{0.5} \left(\frac{\rho_w}{\rho_b} \right)^{0.3} \left(\frac{\overline{c_p}}{c_{pb}} \right)^{n}$$





System Modeling

■ Global model

- Pinch point location is determined by the vapor generator model

Part	Items	Values
Heat source	Inlet temperatures (^{o}C)	160, 170, 180, 190
	Mass flow rate (kg/s)	1
	Pipe pressure (MPa)	1.3
cycle	Pinch point temperature (K)	10
	Condensing temperature (K)	303.15
	Isentropic pump efficiency	0.65
	Isentropic turbine efficiency	0.85

Results

1 W_{net}, η_{th} → 2 A_{total} → 3 Working fluid selection criterion

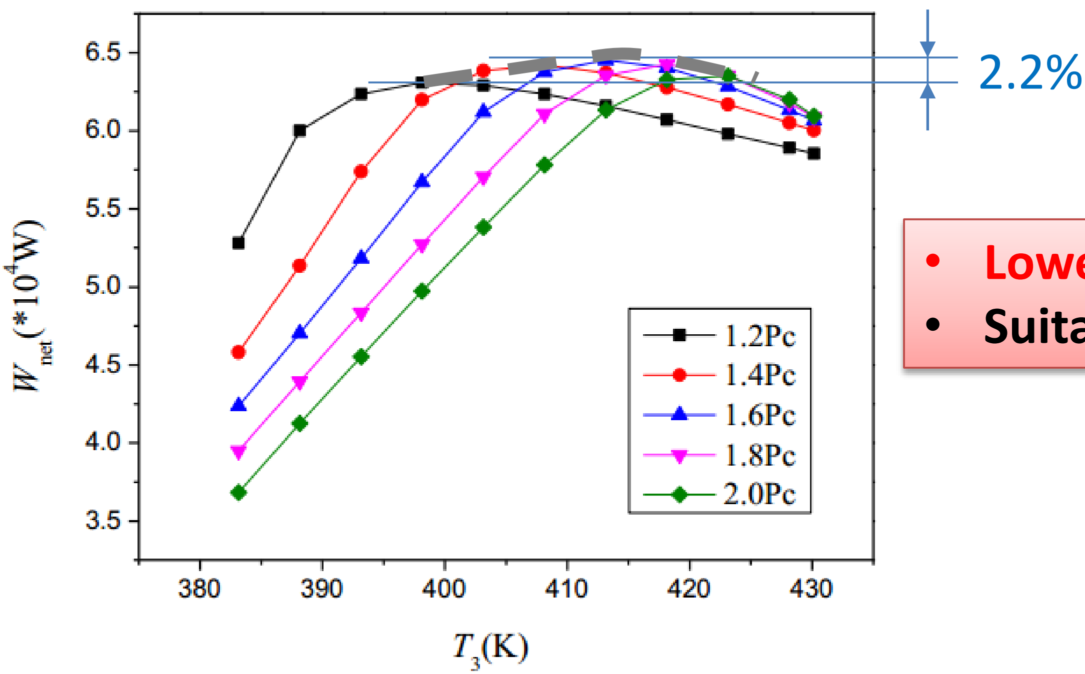
R134a
Heat source: 170℃

1. T_3, P_{vap} are optimized using W_{net}, η_{th}
2. A_{total} were analyzed based on thermophysical property changes
3. Developed a working fluid selection criterion based on the analysis of A_{total} and pinch point location

R134a, R152a, R245fa
HS： 160-190℃

■ Net work output analysis

- There exist a peak of *W*net with *T*3 increases at constant pressure.
- The peak move towards higher *T*3 with *P*vap increasing.
- The peak value difference at various *P*vap is small

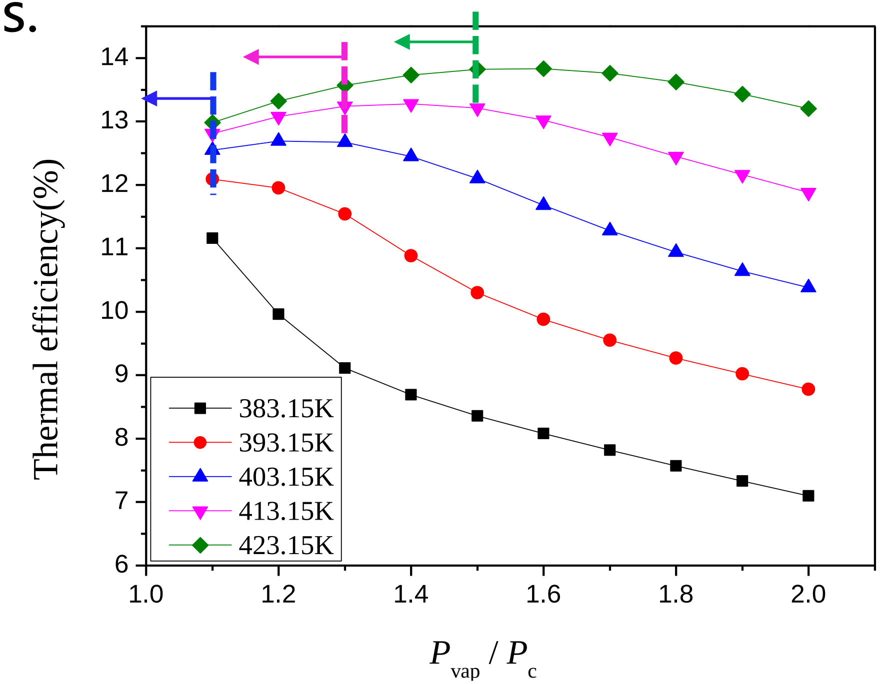


- **Lower *P*vap should be used**
- **Suitable *T*3 range**

■ Thermal efficiency analysis

- The η_{th} increases with *T*3
- The η_{th} variations with *P*vap

1. For lower *T*3, the thermal efficiency decreases with *P*vap
2. For higher *T*3, there exist maximum thermal efficiency as *P*vap increases.



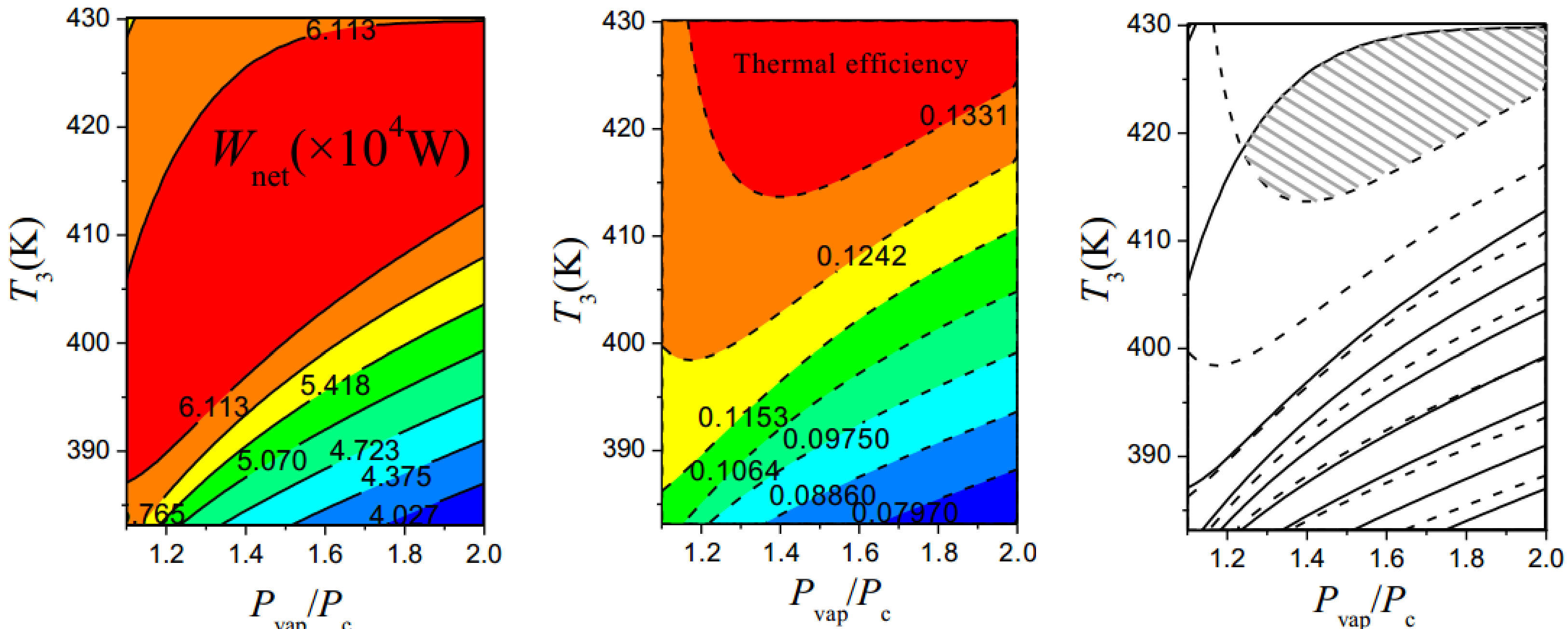
- High *T*3
- High *P*vap

- Two indicators:

$$W_t = Q \cdot \eta_{th}$$

- *W*net—final earnings
- Thermal efficiency—use of the heat source

- Optimal region for both Wnet and thermal efficiency



$94.7\% W_{net,max}$ (a)

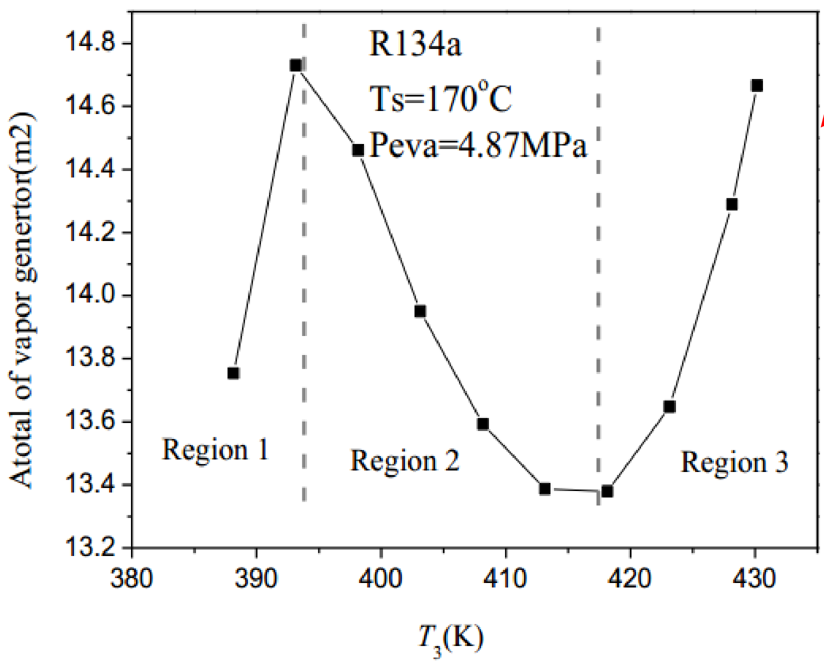
$93.9\% \eta_{th,max}$ (b)

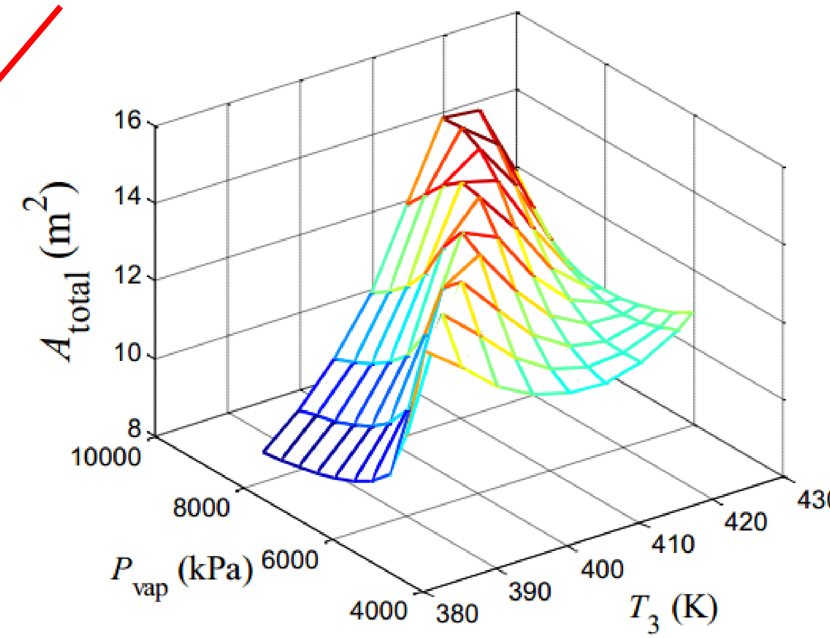
(c)

A_{total} ← Heat transfer at supercritical pressure ← Variations of thermophysical properties →

- Temperature profile
- Pinch point location
- Cycle performance

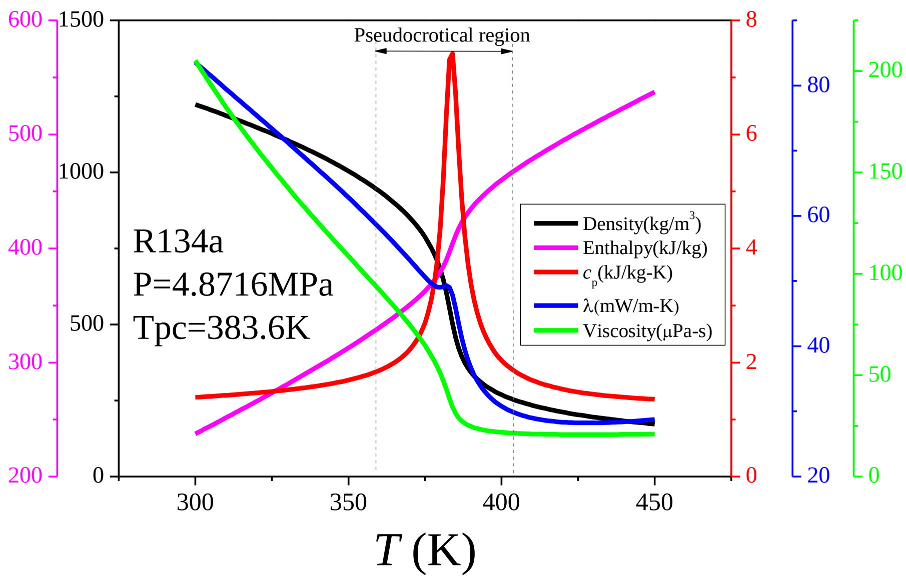
Why

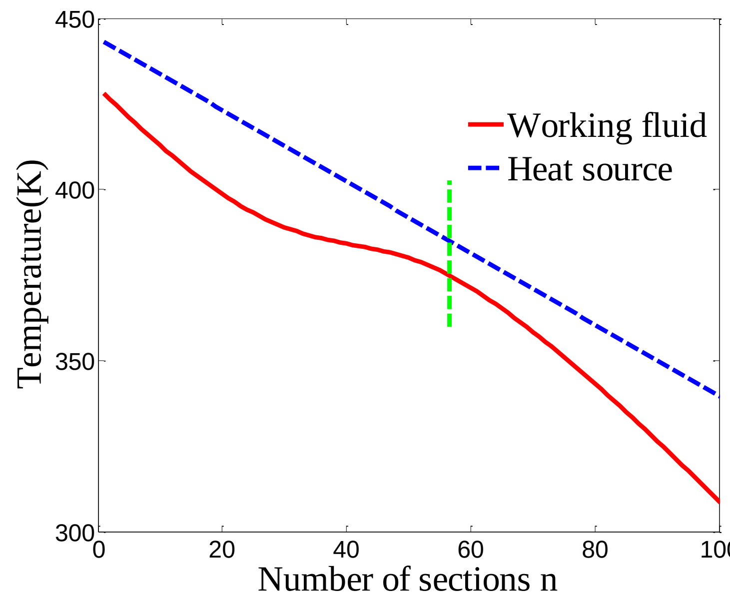




■ Temperature profile

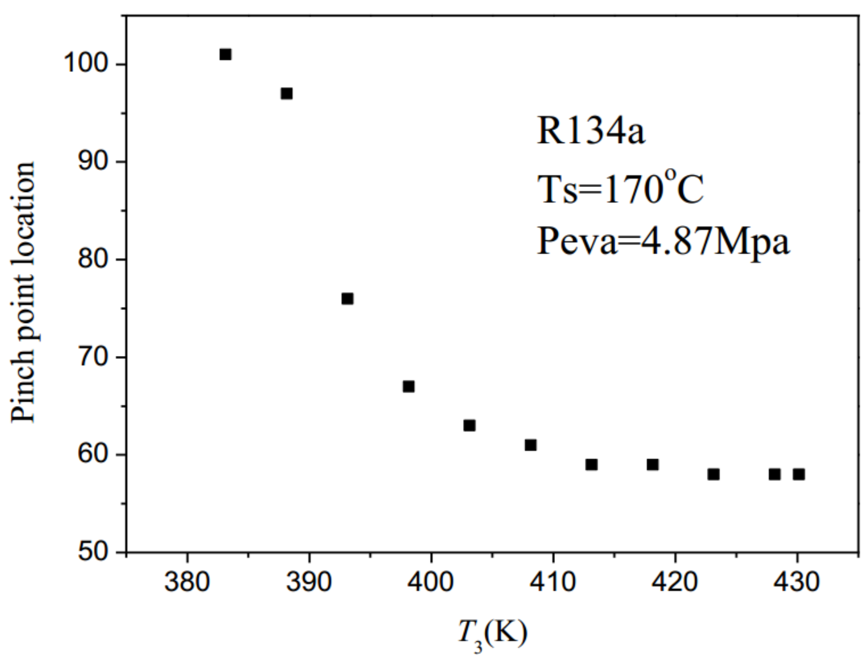
- Enthalpy increases rapidly in the pseudocritical region
- Temperature gradient is much smaller in the pseudocritical region than other two parts
- Influence the pinch point location

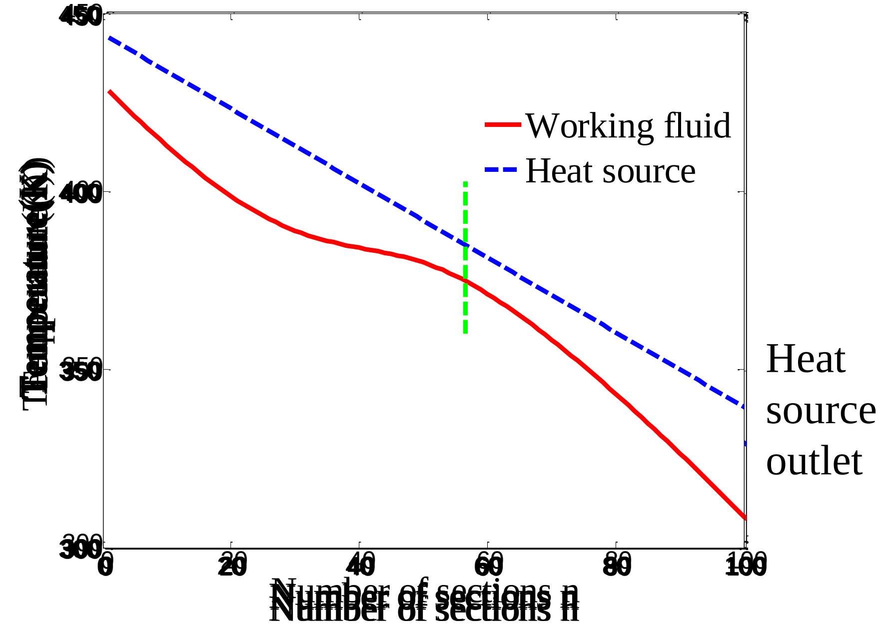




■ The pinch point location

- The pinch point moves from the heat source outlet to the middle with increasing T_3
- The pinch point cannot move across the pseudocritical region



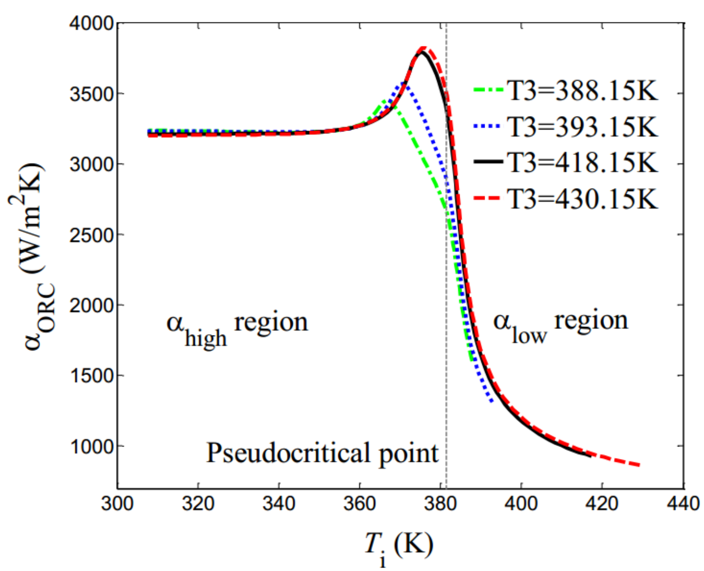


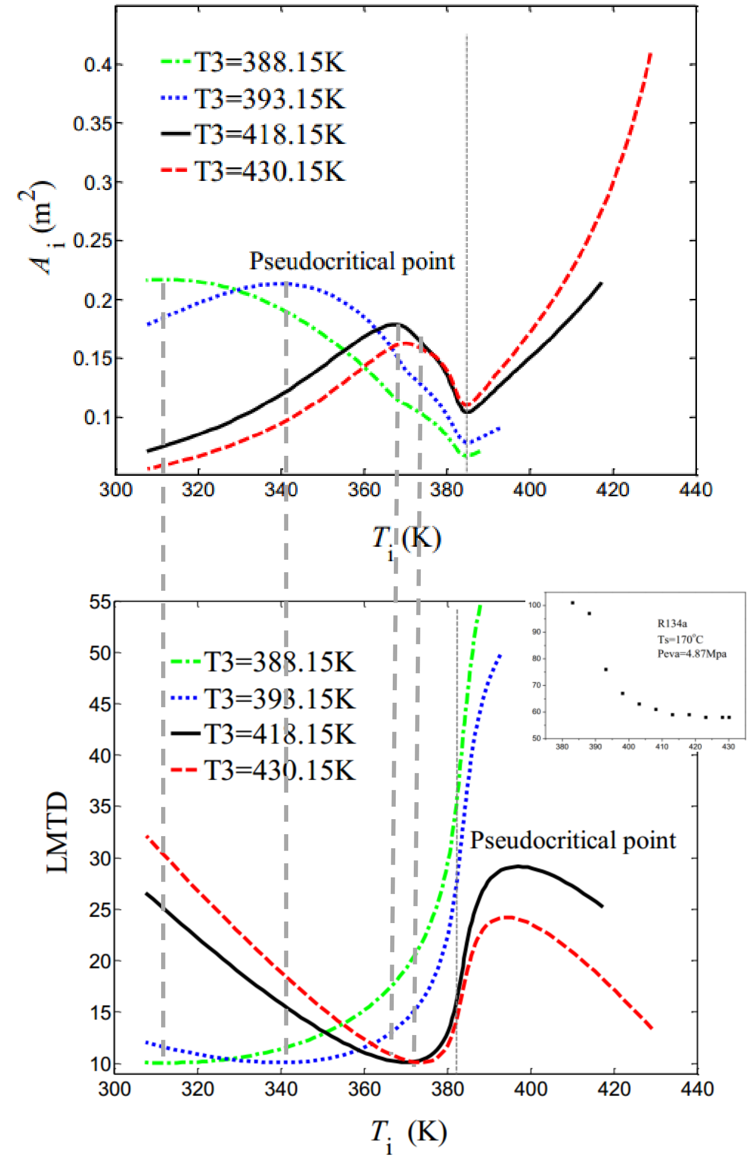
$$Ai = \frac{\Delta h}{\alpha_{ORC} \cdot \mathrm{LMTD}}$$

α_{high} region

Pseudocritical point

α_{low} region





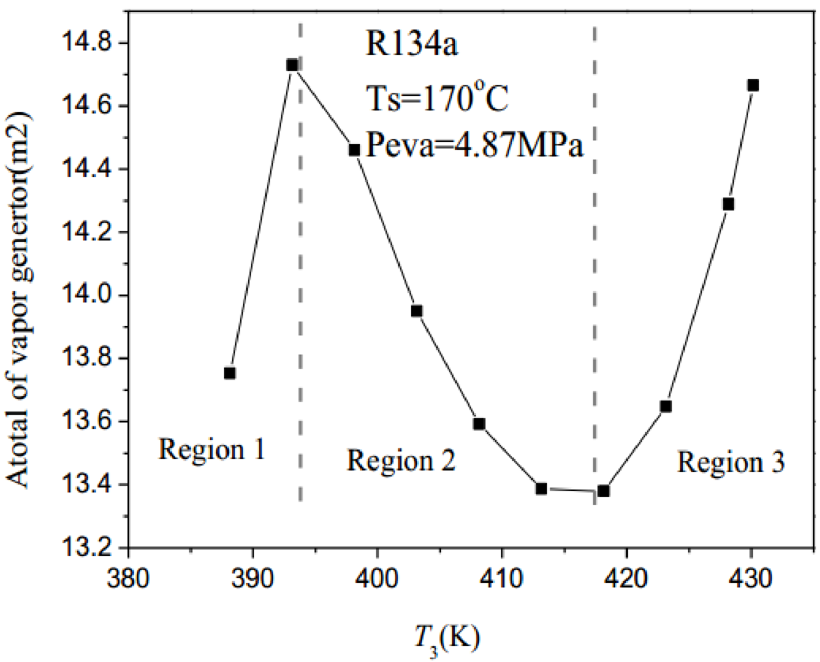
■ Three region of the N-shaped curve

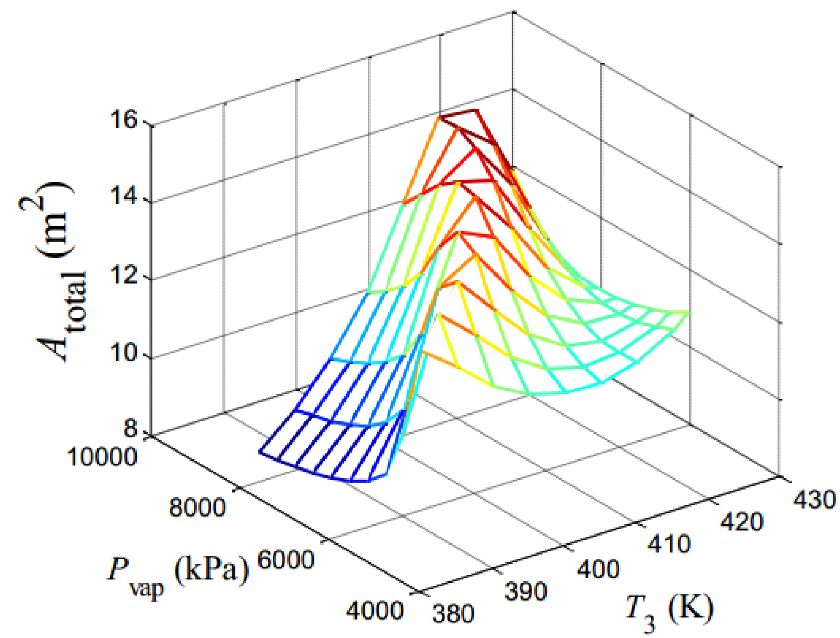
- Recommend region 2

■ Pressure influence

- High pressures are not economic

Region	Atotal	Thermal efficiency
1	Low	Low
2	Low	High
3	High	High





■ Final optimal area

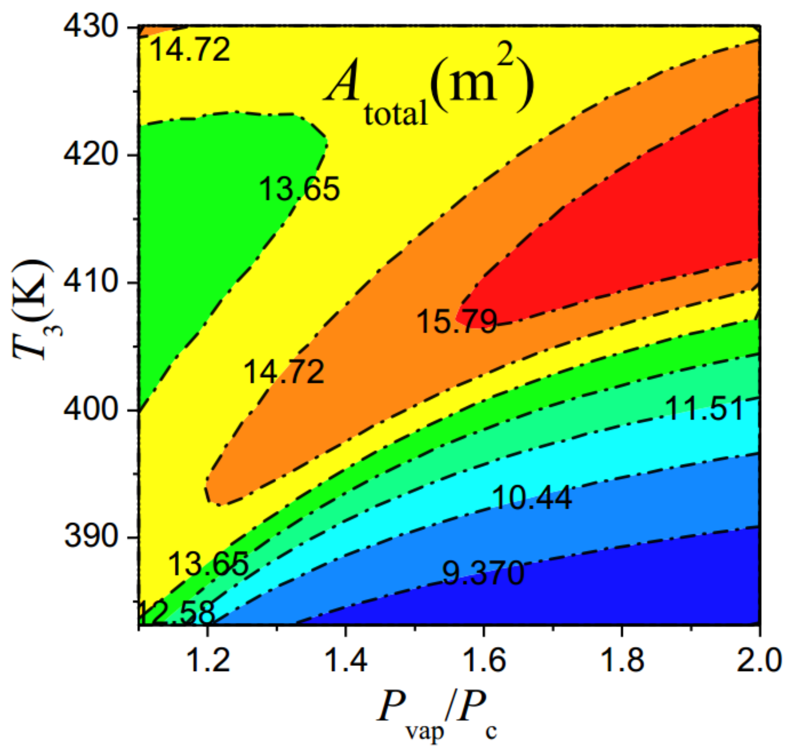
Consider three indicators: W_{net}, η_{th}, A_{total}

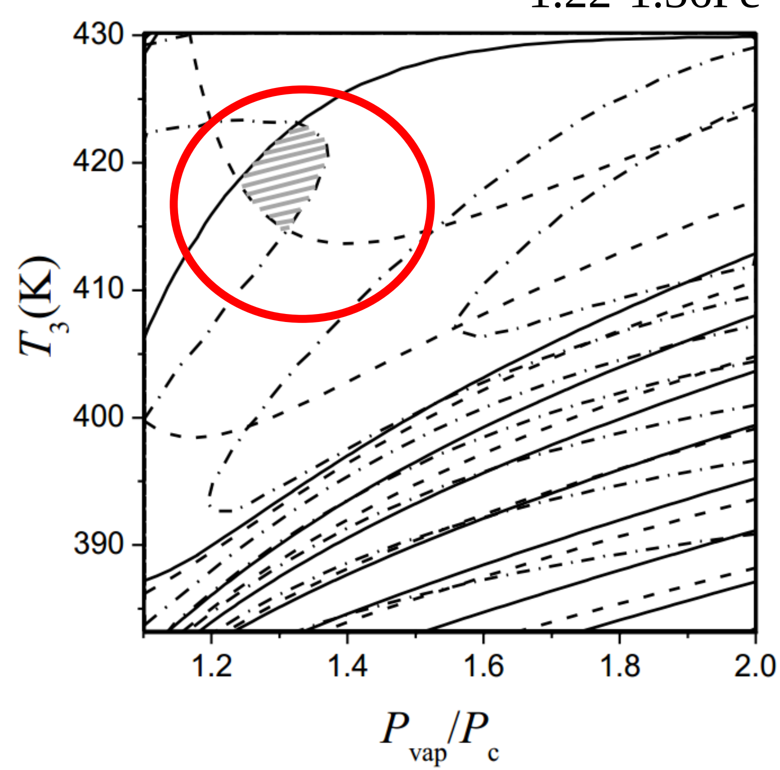
$W_{net} > 94.7\% W_{net,max}$ $\eta_{th} > 93.9\% \eta_{th,max}$

A_{total} is 19.3% smaller than the $A_{total,max}$

415-423K

1.22-1.36Pc





- Change heat source inlet temperature *Ts*

	T_c (°C)	P_c (MPa)	T_s (°C)	$W_{net,max}$ (kW)	P_{vap} (MPa)	η_{th} (%)
R134a	101.06	4.0593	160	55.4	6.089	12.10
			170	64.5	6.495	13.02
			180	73.9	6.901	13.76
			190	83.4	7.713	14.29
R152a	113.26	4.5168	180	73.5	6.324	13.85
			190	83.6	6.775	14.70
R245fa	154.01	3.651	190	90.4	4.746	15.22

When *Ts*>>*Tc*, much higher P_{vap} is needed

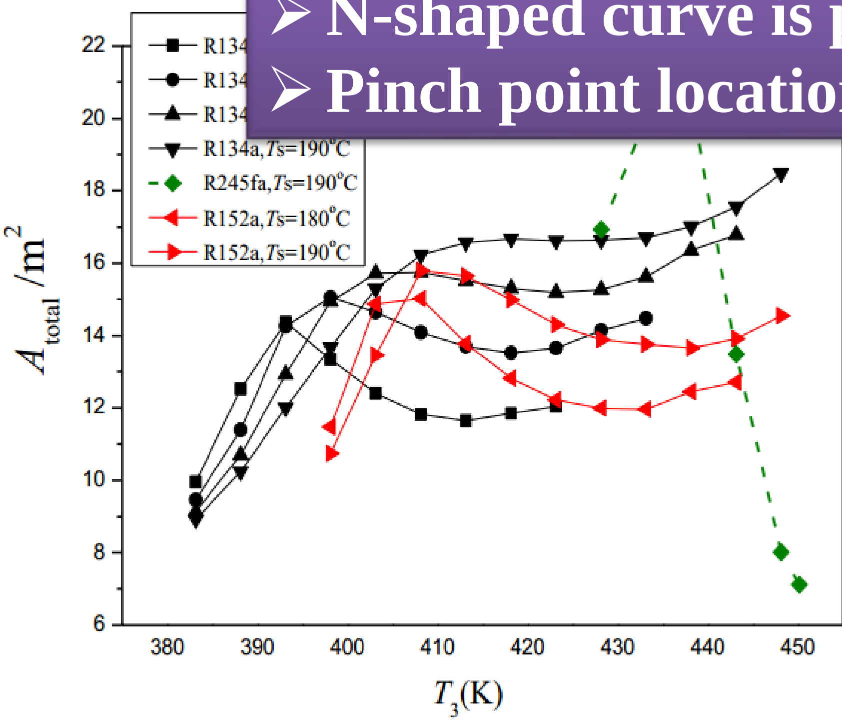
■ Working fluid selection criterion: for different heat source temperature

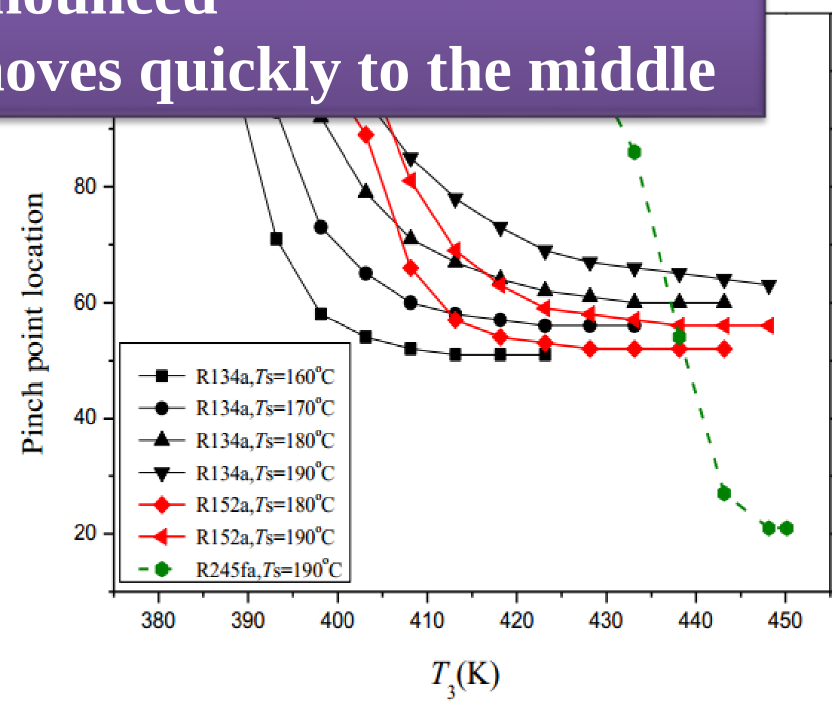
- Pressure high
- A_{total} high
- No optimal area

→ Working fluid with higher Tc are suggested

Working fluid selection criterion :

- ➢ **N-shaped curve is pronounced**
- ➢ **Pinch point location moves quickly to the middle**





Conclusions

1. Significant changes of the thermophysical properties greatly affect the performance of supercritical ORCs . The heat transfer mechanisms at supercritical pressure must be further understood for system optimization and proper heat exchanger design.

2. *A_{total} varies with T_3 along an N-shaped curve* due to the variations of HTC, LMTD and the pinch point location movement. Operating conditions should be in region 2 of the N-shaped curve to give the optimal area with the best W_{net} and thermal efficiency.

3. Working fluid selection criterion for various heat source temperature:
   - A suitable working fluid should have a pronounced N-shaped curve for A_{total} to guarantee the existence of the optimal parameter region.
   - Pinch point location moves quickly from heat source outlet to the middle

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