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Thermo-economic comparison of organic Rankine and CO_2-cycle systems for low-to-medium temperature applications

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Outline

- ❑ Background
- ❑ System description
- ❑ Calculation models
- ❑ Comparison results
- ❑ Conclusions

Background

Heat-to-power conversion: Low-to-medium grade heat (<300 °C)

- ❑ Heat source

  geothermal, biomass, solar, industrial waste heat

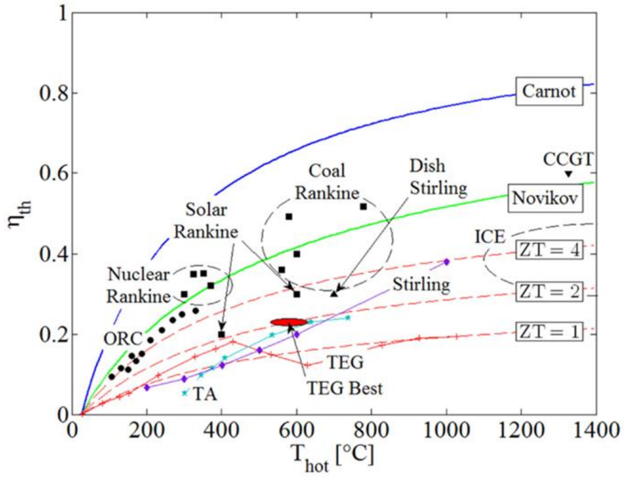
- ❑ Technology
  - Organic Rankine cycle (ORC)

    High efficiency, reliable and available;

    Environmental and safety issues
  - CO_2 power cycle (transcritical: CTPC; supercritical)

    Environmental-friendly, compact; high decomposition temperature

    Low efficiency, high-pressure



[1] Markides CN, Low concentration solar-power systems based on organic Rankine cycles for distributed-scale applications: overview and further developments. Front Energy Res 2015;3:47.

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Technology comparison and selection

Li et al. 2014

Geothermal 90-120 °C
CTPC vs ORC (R123, R245fa, R600a, R601)
Basic cycle & recuperative cycle
R600a-ORC shows best W_{net}

Klemencic et al. 2016

Cement plant waste heat 295 °C/ 410 °C
CTPC vs sCO_2 vs ORC (Cyclopentane)
Basic cycle & recuperative cycle
CTPC shows best W_{net} and η_{th}

Li et al. 2016

Waste heat 120-260 °C
CTPC vs ORC (R245fa)
Basic cycle & recuperative cycle
R245fa-ORC outperforms CTPC in η_{th}

Shu et al. 2016

Engine waste heat 780 °C
CTPC vs ORC (R123)
Basic cycle & preheated-recuperative cycle
CTPC outperforms in economic

Astolfi et al. 2019

200-600 °C
CO_2 systems vs ORC (47 WFs)
Basic & recuperative & cascade & …
>300 °C CO_2; <300 °C ORC in η_{th}

Scientific gap:
ORC vs CO_2 cycle

System description

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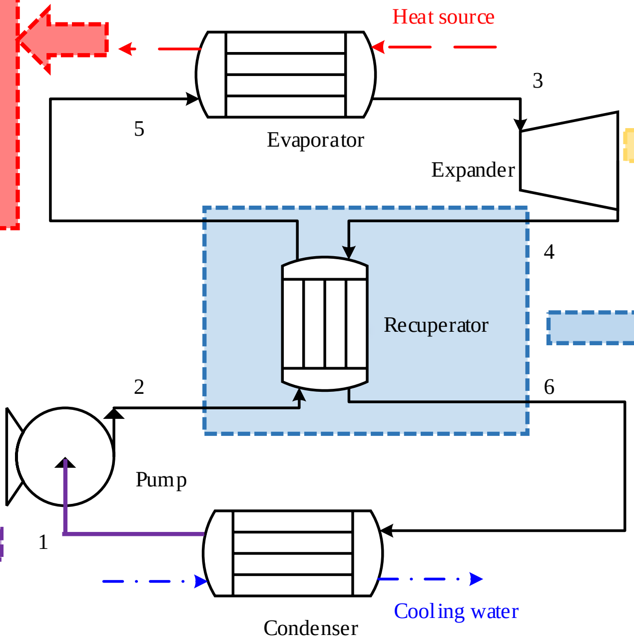
- Geothermal:
100-200 °C, 15-50 kg/s
- Engine exhaust
200-300 °C, 20-120 kg/s

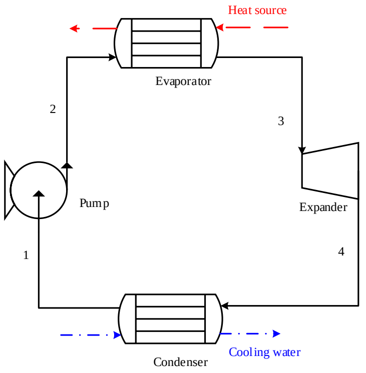


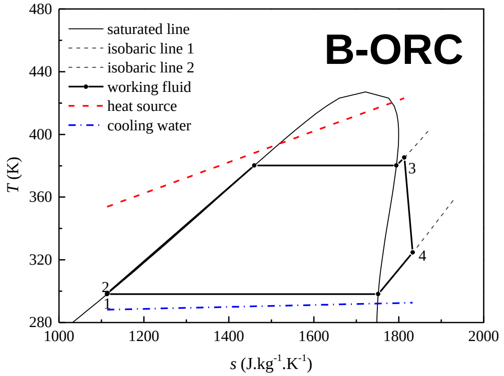
- Reciprocating-piston
- Radial-inflow turbine

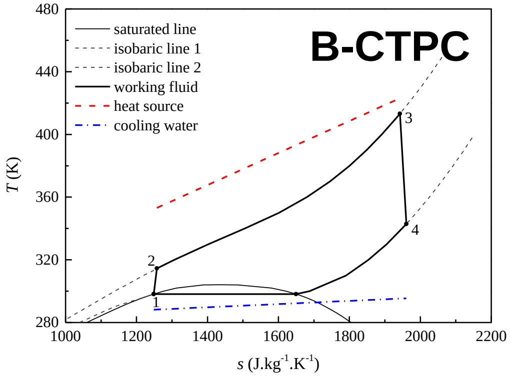
- Basic cycle
- Recuperative cycle

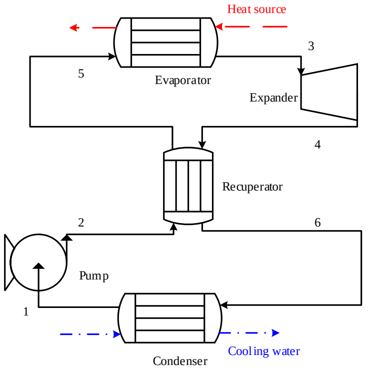
- R245fa
- R600
- R1233zd
- CO_2

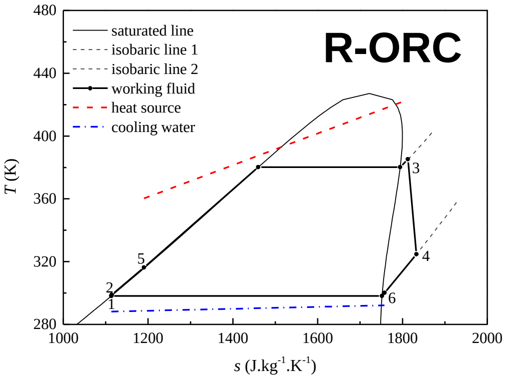
System description

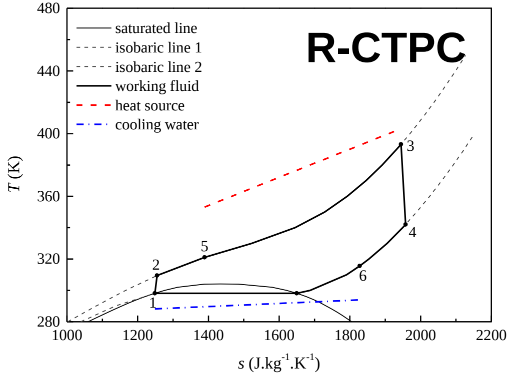












Calculation models

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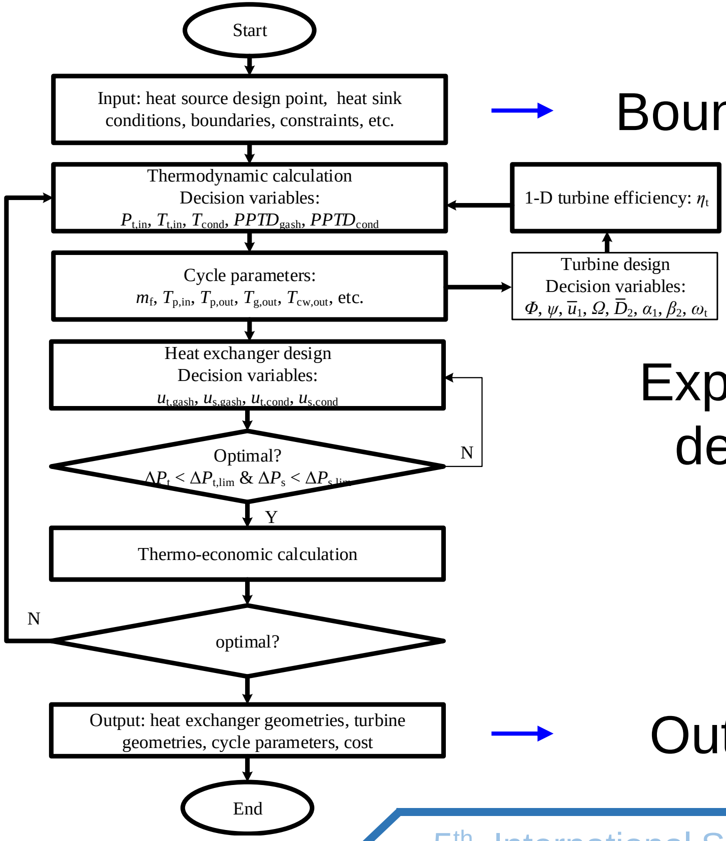
Overall thermo-economic model

Cycle parameters determination

Heat exchanger design

Economic performance evaluation



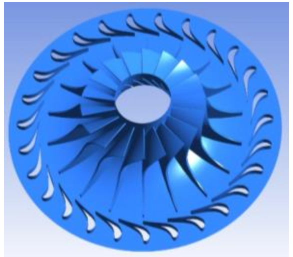
Boundary

Expander design

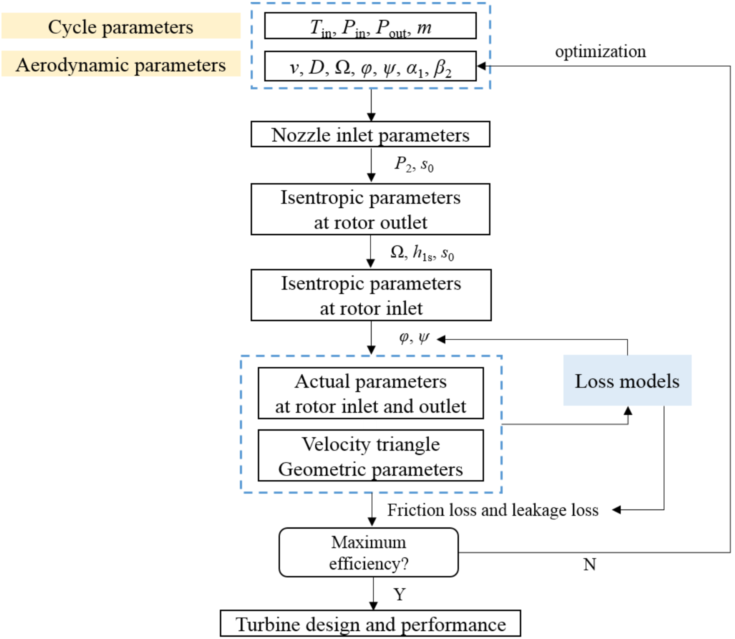
Output

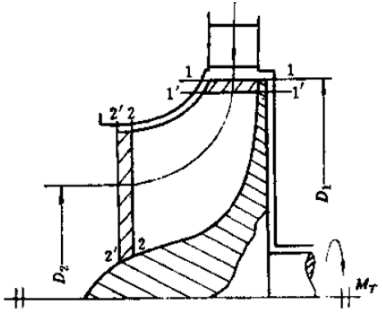
Calculation models

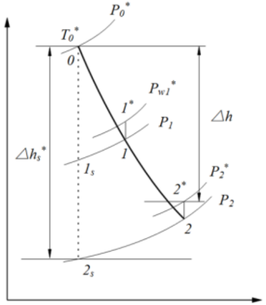
Expansion device – Radial-inflow turbine

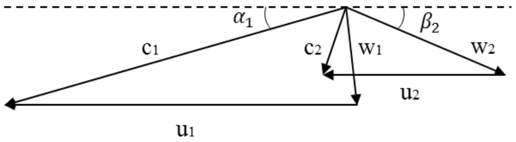


1-D mean-line method + loss models









[1] Song et al. Influence of the radial-inflow turbine efficiency prediction on the design and analysis of the organic Rankine cycle (ORC) system. Energy Convers Manag 2016;123:308-16.

Calculation models

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Expansion device – Reciprocating-piston expander

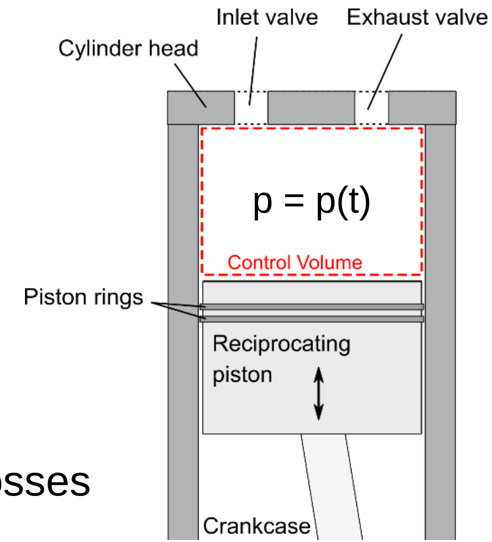
Lumped-mass model

- Dynamic lumped model in MATLAB
  - Conserving mass and energy:

$$\frac{\mathrm{d}m}{\mathrm{d}t} = \dot{m}_{\mathrm{in}} - \dot{m}_{\mathrm{out}}$$

$$\frac{\mathrm{d}}{\mathrm{d}t}(mh) = \dot{Q} + V\frac{\mathrm{d}P}{\mathrm{d}t} + \sum \dot{m}_{\mathrm{in}} h_{\mathrm{in}} - \sum \dot{m}_{\mathrm{out}} h_{\mathrm{out}}$$

  - Heat transfer using correlations
  - Loss models: in-cylinder, pressure, mechanical power losses
- Maps of optimal designs for given conditions
  - Output power, efficiency and mass flow rate given as function of inlet pressure and temperature.

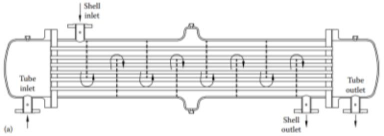


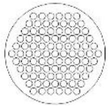
[1] Sapin P, Taleb A, White AJ, Markides CN. Reciprocating-piston compressors or expanders for energy-conversion or energy-storage applications. In: Proc. of the 4th Sustainable Thermal Energy Mgmt Intl Conf (SusTEM2017). Alkmaar, the Netherlands; 2017.

Calculation models

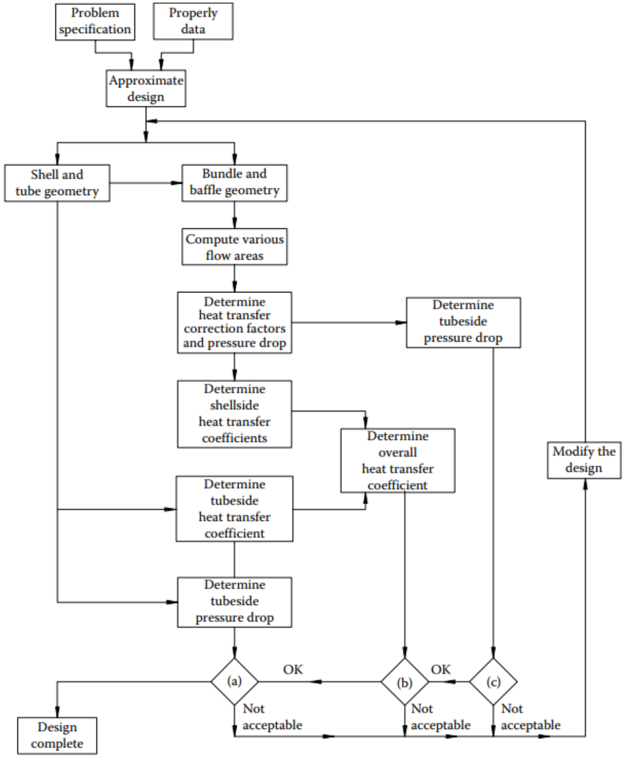
Heat exchanger – Shell-and-tube type

Bell-Delaware method





- Shell side
  - HTC $$\alpha_s = j_i \frac{c_{p,s} G_s}{\mathrm{Pr}_s^{2/3}} \left(\frac{\mu_s}{\mu_w}\right)^{0.14} j_c j_l j_b j_s j_r$$
  - ΔP $$\Delta P_s = \left[(N_b - 1) R_b R_l + 2\left(1 + \frac{N_{tcw}}{N_{tcc}}\right) R_b R_s\right] \frac{2 f_s N_{tcc} G_s^2}{\rho_s} \left(\frac{\mu_s}{\mu_w}\right)^{-0.14} + \frac{(2 + 0.6 N_{tcw}) G_w^2}{2\rho_s} N_b R_l$$
- Tube side
  - HTC – different correlations
  - ΔP $$\Delta P_t = \frac{1.5 G^2}{2\rho} + \frac{f_t L G^2 Z_t}{2 d_i \rho \varphi_t} + \frac{G^2}{2\rho}(K_c + K_e) Z_t + \frac{4 Z_t G^2}{2\rho}$$
- Overall HTC $$\frac{1}{K} = \frac{1}{\alpha_t} \cdot \frac{d_o}{d_i} + r_{ft} \cdot \frac{d_o}{d_i} + \frac{\delta_w}{\lambda_w} \cdot \frac{d_o}{d_m} + r_{fs} + \frac{1}{\alpha_s}$$
- HTX area $$A = \frac{Q}{K \cdot \mathrm{LMTD}} \qquad \mathrm{LMTD} = \frac{(T_{h,in} - T_{c,out}) - (T_{h,out} - T_{c,in})}{\ln\left[(T_{h,in} - T_{c,out}) / (T_{h,out} - T_{c,in})\right]}$$



[1] Thulukkanam K. Heat exchanger design handbook. CRC press; 2013.

Calculation models

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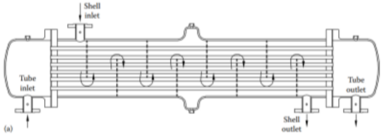
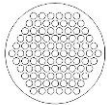
Heat exchanger – Shell-and-tube type

Bell-Delaware method





- Correlations for tube-side HTC calculation

	Phase	Correlation	Formula
ORC	Single phase	Dittus-Boelter	$\alpha_t = 0.023 \cdot \frac{\lambda}{d_i} \mathrm{Re}^{0.8} \cdot \mathrm{Pr}^{n}$
ORC	Evaporation	Cooper nucleate pool-boiling	$\alpha_t = 1.5 \cdot 55 \cdot \left(P_{evap}/P_{crit}\right)^{\left[0.12-0.2\cdot\log\left(R_p\right)\right]} \cdot \left[-\log(P_{evap}/P_{crit})\right]^{-0.55} \cdot q^{0.67} \cdot M_r^{-0.5}$
ORC	Condensation	Dobson	$\alpha_t = 0.023 \cdot \frac{\lambda}{d_i} \cdot \mathrm{Re}_l^{0.8} \cdot \mathrm{Pr}_l^{0.4} \cdot \left(1 + \frac{2.22}{X_{tt}^{0.89}}\right)$
CTPC	Single phase	Petukhov-Kirillov	$\alpha_t = \frac{\lambda}{d_i} \frac{(f/8)\mathrm{Re}\,\mathrm{Pr}}{\left[12.7(f/8)^{0.5}(\mathrm{Pr}^{2/3}-1)+1.07\right]}$
CTPC	Supercritical	Petukhov-Krasnoshchekov-Protopopov	$\alpha_t = \frac{\lambda}{d_i} \frac{(f/8)\mathrm{Re}\,\mathrm{Pr}}{\left[12.7(f/8)^{0.5}(\mathrm{Pr}^{2/3}-1)+1.07\right]} \left(\frac{\bar{c}_p}{c_{pbulk}}\right)^{0.35} \left(\frac{\lambda_{bulk}}{\lambda_{wall}}\right)^{-0.33} \left(\frac{\mu_{bulk}}{\mu_{wall}}\right)^{0.11}$
CTPC	Condensation	Chen	$\alpha_t = 0.023 \frac{\lambda}{d_i} \mathrm{Re}^{0.8} \mathrm{Pr}^{0.4} F$

[1] Shu et al. An improved CO_2-based transcritical Rankine cycle (CTRC) used for engine waste heat recovery. Appl Energy 2016;176:171-82.
[2] Thulukkanam K. Heat exchanger design handbook. CRC press; 2013.

Calculation models

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Economic models – Cost estimation

Module costing technique

$$C_{BM} = C_p^0 F_{BM} = C_p^0 (B_1 + B_2 F_M F_P)$$

$$\log(C_p^0) = K_1 + K_2 \log(X) + K_3 [\log(X)]^2$$

$$\log(F_p^0) = C_1 + C_2 \log(P_i) + C_3 [\log(P_i)]^2$$

$$Cost = \sum C_{BM} \frac{CEPCI_{2017}}{CEPCI_{2001}}$$

$$SIC = \frac{Cost}{W_n}$$

Constant	Heat exchanger	Pump	Turbine	Piston
K_1	4.3247	3.8696	2.2476	2.7051
K_2	-0.303	0.3161	1.4965	1.4398
K_3	0.1634	0.122	-0.1618	-0.1776
C_1	-0.0016	-0.2454	/	/
C_2	-0.0063	0.259	/	/
C_3	0.0123	-0.0136	/	/
B_1	1.63	1.89	/	/
B_2	1.66	1.35	/	/
F_M	1.35	1	/	/
F_{bm}	/	/	3.5	3.5

[1] Turton R, Bailie RC, Whiting WB, Shaeiwitz JA. Analysis, synthesis and design of chemical processes. Pearson; 2008.

Comparison results

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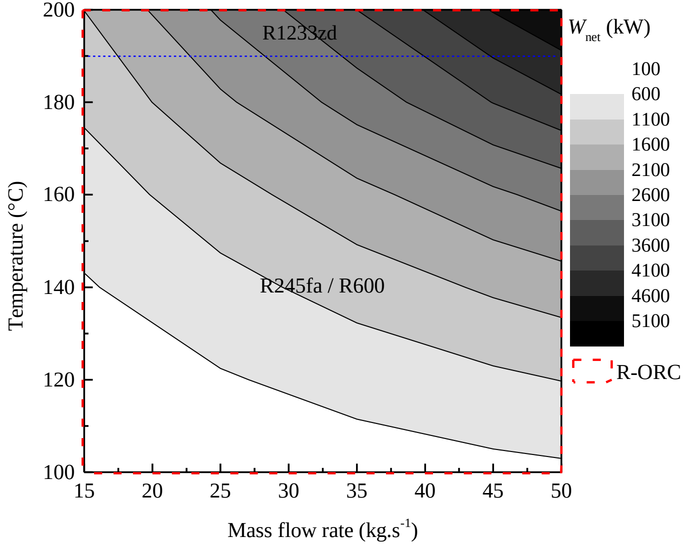
Geothermal application – with radial-inflow turbine

Net power output



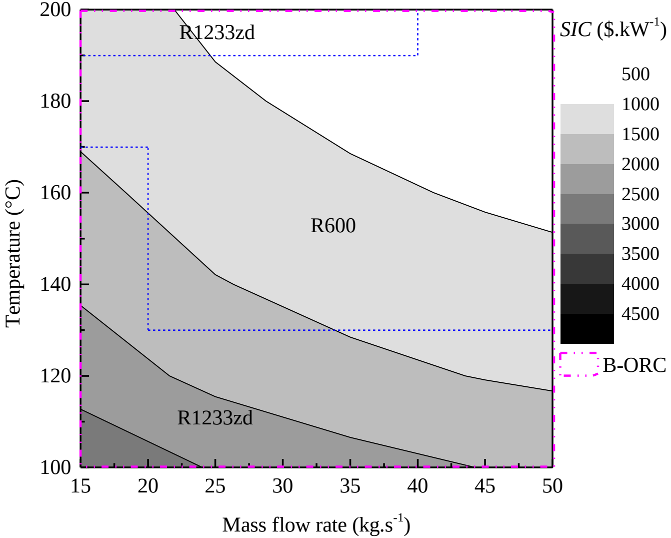
R-ORC is the best

- Low heat source temperature; η_t = ~0.84

WF varies with HS temp., not remarkable

- similar critical temp. (~425-435 K)

Specific investment cost



B-ORC is the best

- similar W_{net} with R-ORC; no recuperator cost

Comparison results

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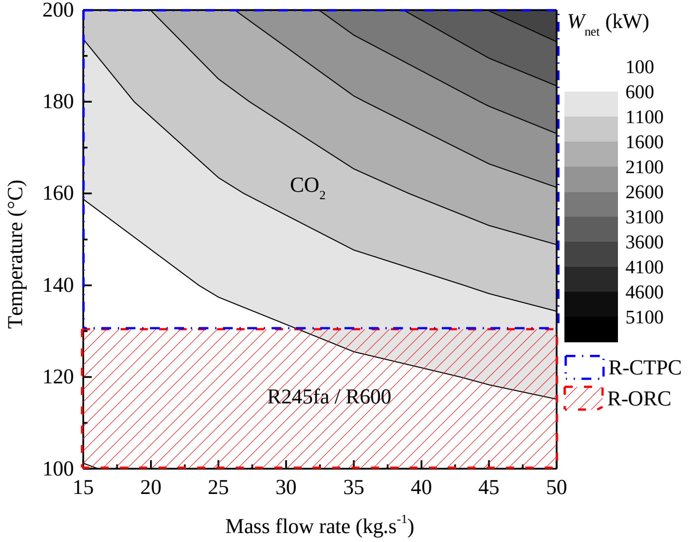
Geothermal application – with reciprocating-piston expander

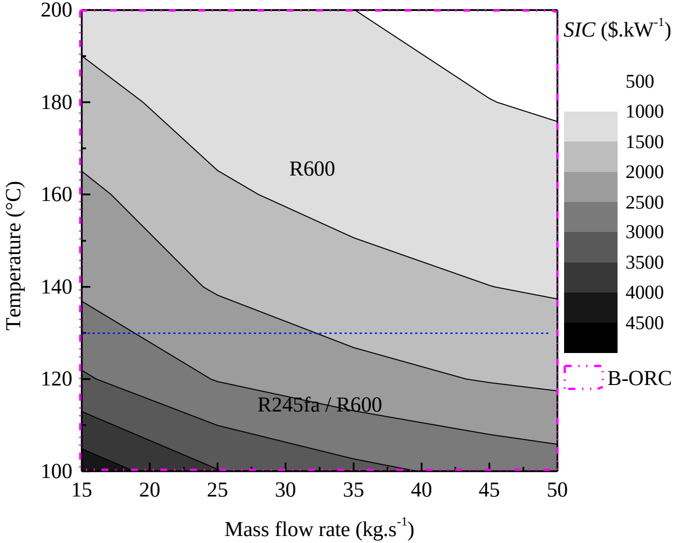
Net power output



<130 °C: R-ORC; >130 °C: R-CTPC

- piston isentropic efficiency *vs* pressure ratio
- better temperature match

Specific investment cost



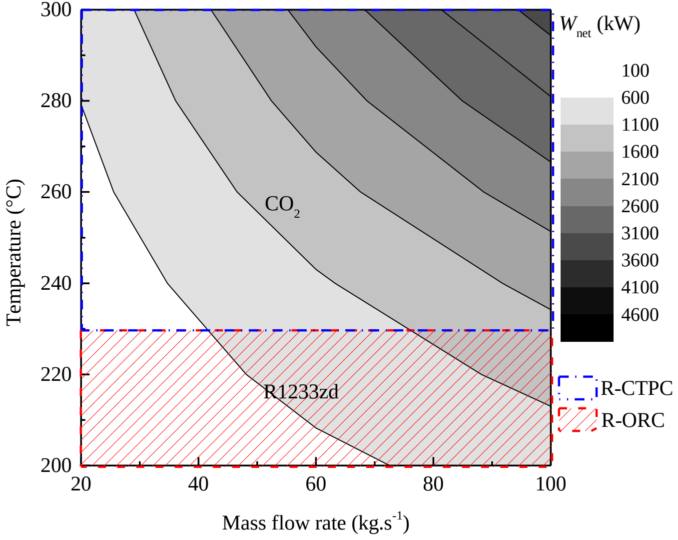
B-ORC is the best

- R600; less HTX areas

Comparison results

Marine engine WHR – with radial-inflow turbine

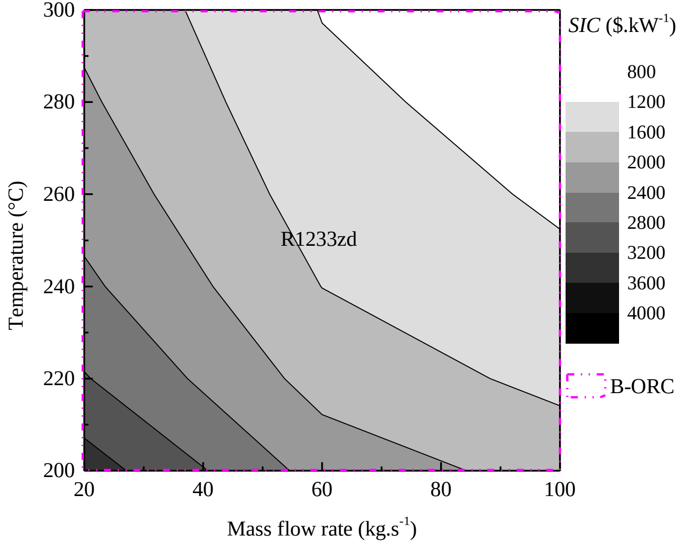
Net power output



<230 °C: R-ORC; >230 °C: R-CTPC

- better temperature match

Specific investment cost



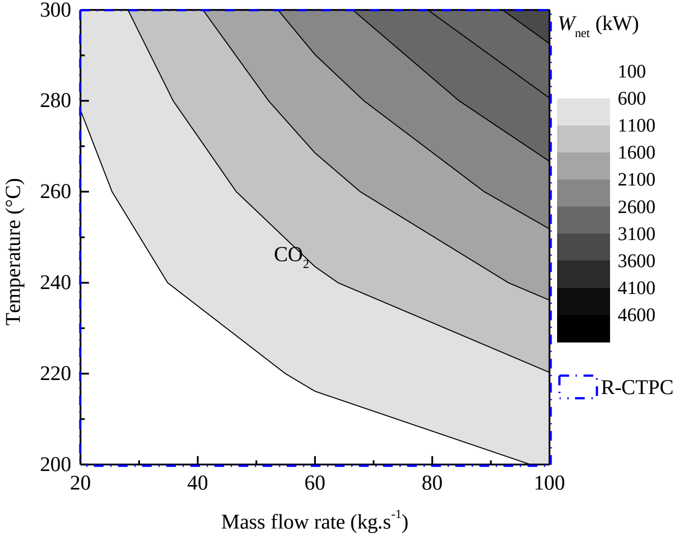
B-ORC is the best

- similar W_{net} with R-ORC; no recuperator cost
- pump cost in CTPC is higher
- R1233zd

Comparison results

Marine engine WHR – with reciprocating-piston expander

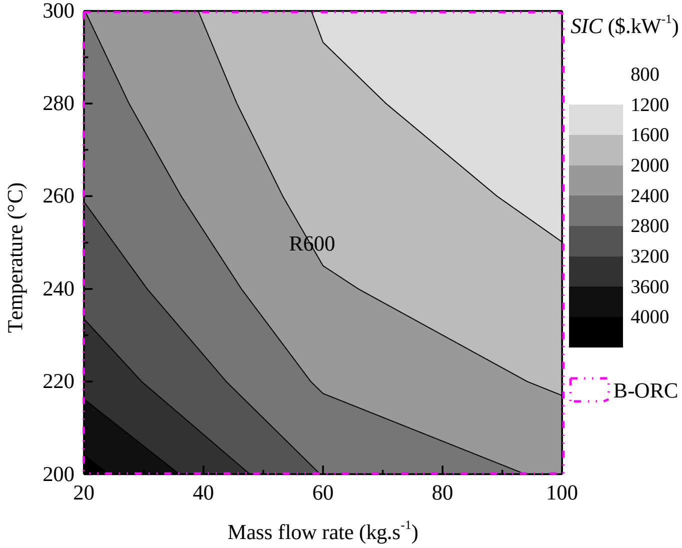
Net power output



R-CTPC is the best

- better temperature match
- higher expander isentropic efficiency

Specific investment cost



B-ORC is the best

- similar W_{net} with R-ORC; no recuperator cost
- pump cost in CTPC is higher
- R600

Comparison results

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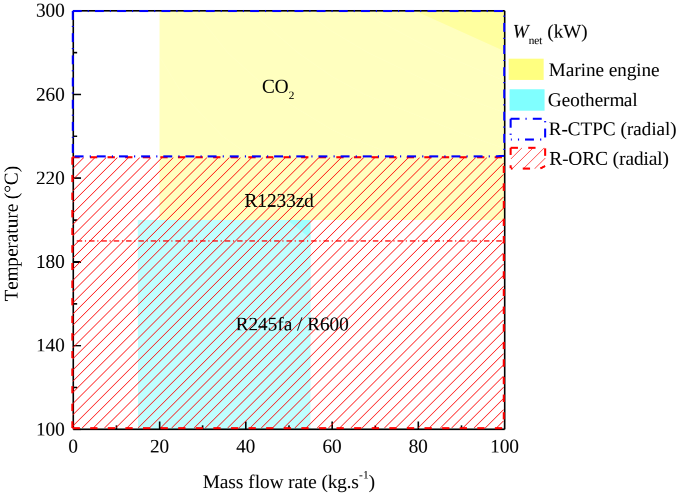
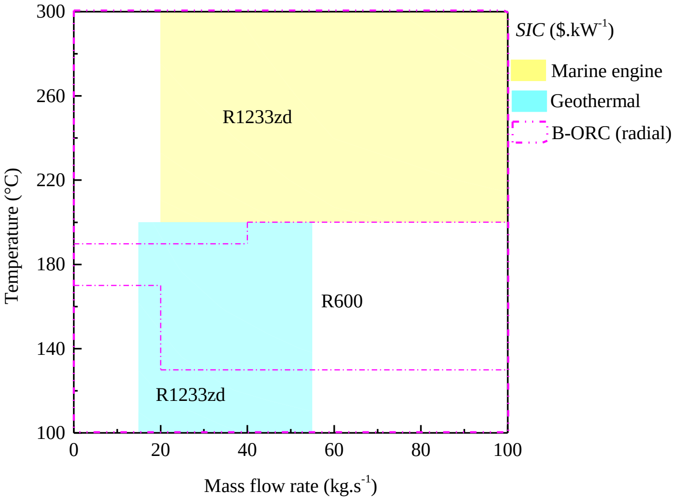
Generalized selection maps

Net power output



Specific investment cost



Recuperator is preferable
CO_2 systems are better at higher HS temp.
Radial-inflow turbine outperforms

B-ORC is the best

Conclusions

- Thermodynamic and economic performance selection maps are generated through comprehensive component-to-system level comparison
- A recuperator is favoured for high power outputs, while basic systems are more economically viable. R-CTPC system outperforms the other systems at higher heat-source temperatures, while R-ORC system is much more suitable at lower heat-source temperatures in terms of net power output
- Optimal working fluid in ORC systems is much more sensitive to the heat-source temperature than to the heat-source mass flow-rate
- Radial-inflow turbines appear more attractive than reciprocating-piston expanders for the given applications

Thanks for your attention!

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