Thermoeconomic analysis of recuperative sub- and transcritical organic Rankine cycle systems

Oyeniyi A. Oyewunmi, Steven Lecompte, Michel De Paepe, and Christos N. Markides

Clean Energy Processes (CEP) Laboratory
Department of Chemical Engineering
Imperial College London
South Kensington Campus, London, SW7 2AZ, UK
Outline

- Introductory background – ORC system configurations/architectures
- Model and optimization algorithm
- Results – Effect of evaporation pressure
- Results – Subcritical and transcritical systems
- Results – Condenser boundary conditions
- Conclusions
ORC system configurations/architectures

- Subcritical systems
- Transcritical systems
- Trilateral, partial evaporative, and other systems
- Recuperative ORC systems?
Model and algorithm – thermodynamic model

- Energy balances:

- Recuperator:

\[ \theta_{\text{recup}} = \frac{T_4 - T_{4r}}{T_4 - (T_2 + \Delta T_{\text{min}})} \approx \frac{h_4 - h_{4r}}{h_4 - h(T_2 + \Delta T_{\text{min}}, P_{\text{evap}})} \]

\[ \theta_{\text{recup}} \approx 0 \rightarrow \text{No recuperation, } T_4 = T_{4r}, T_2 = T_{2r} \]

\[ \theta_{\text{recup}} > 0 \rightarrow \text{Recuperator deployed.} \]

- Assumptions:

  \( \eta_{s, \text{exp}} = 75\% \)
  \( \eta_{s, \text{pump}} = 85\% \)
  \( \Delta T_{\text{min}} = 10 \, ^{\circ}C \)
Model and algorithm – costing model

- Pump, pump motor and expanders are costed using the correlations proposed by Seider et al. and Turton et al.:

\[
C_p^0 = F \exp(Z_1 + Z_2 \ln X + Z_3 \ln(X)^2 + Z_4 \ln(X)^3 + Z_5 \ln(X)^4)
\]

\[
C_p^0 = F 10^{(Z_1 + Z_2 \log X + Z_3 \log(X)^2)}
\]

- Heat exchangers costed with the ‘C-value’ method and the ESDU 92013 chart

- Equipment cost modified to account for high/low pressure effects

- Costs converted to today’s prices using the CEPCI
Boundary conditions and problem definition

- Heat source: Waste-heat flue gas in @ 380 °C and 185 kg/s
- Heat sink: Cooling water in @ 25 °C; out @ 55 °C for a ΔT of 30 °C

- Working fluids (34 in total):
  - 8 × Light hydrocarbons (butane, isobutane, pentane, …)
  - 5 × Heavy & aromatic hydrocarbons (benzene, nonane, decane, …)
  - 16 × Refrigerants (R218, R227ea, R245fa, …)
  - 5 × Siloxanes (D4, D5, MM, MDM, MD2M)

*Thermodynamic properties from Refprop
Boundary conditions and problem definition

- Optimization problem:

  \[
  \text{maximize } \hat{W}_{\text{net}}
  \]

  subject to: \( \Delta T_i \geq \Delta T_{\text{min}}(10 \, ^\circ\text{C}) \) \( \forall \, i \)
  \[T_4 \geq T_{\text{dew}}(P_{\text{cond}})\]
  \[0 \leq \theta_{\text{SH}}, \theta_{\text{recup}} \leq 1\]

  \[P_{\text{evap}} \leq 0.95P_{\text{crit}} \text{ or } P_{\text{evap}} \geq 1.05P_{\text{crit}}\]

  \[P_{\text{cond}} \geq 1 \, \text{atm} \] **
Results: Effect of evaporation pressure (1/2)

Light hydrocarbons

Refrigerants
Results: Effect of evaporation pressure (2/2)

Condensation at atmospheric pressure

\[ P_{\text{cond}} = 1 \text{ atm} \]
Results: Recuperators in subcritical cycles

Fluids with $\theta_{\text{recup}} = 0$

- Pentane, R113, R123, R141b

Fluids with $0 < \theta_{\text{recup}} < 1$

- Propane (0.84), propylene (0.70), R115 (0.66), R12 (0.95), R125 (0.37), R134a (0.90), R143a (0.45), R218 (0.64), benzene (0.21), toluene (0.23)

Fluids with $\theta_{\text{recup}} = 1$

- Butane, isobutane, hexane, iso-hexane, heptane, octane, nonane, R114, R124, R142b, R152a, R127ea, R245fa, RC318, D4, D5, MM, MDM, MD2M

P_{\text{evap}} = 0.95P_{\text{crit}}

A few slightly dry fluids; 4 out of 34

- All wet fluids due to superheating required
- Heavy fluids due to condensation limit at 1 atm
Results: Recuperators in transcritical cycles

- More fluids (16) no longer require recuperator
- A few refrigerants
- Heavy fluids due to condensation limit at 1 atm

Fluids with $\theta_{\text{recup}} = 0$
- Propane, butane, isobutane, pentane, propylene, R113, R114, R12, R123, R124, R134a, R141b, R142b, R143a, R152a, R245fa

Fluids with $0 < \theta_{\text{recup}} < 1$
- Isohexane (0.80), benzene (0.01), toluene (0.06)

Fluids with $\theta_{\text{recup}} = 1$
- Hexane, heptane, octane, nonane, decane, R115, R125, R218, R227ea, RC318, D4, D5, MM, MDM, MD2M

$P_{\text{evap}} \leq 0.95P_{\text{crit}}$

$P_{\text{evap}} \geq 1.05P_{\text{crit}}$
Results: Costs of sub- and transcritical systems

- Systems with transcritical cycles are generally more expensive
- High pressure systems ($P_{\text{evap}} \geq 150\text{ bar}$) are heavily penalised
- Systems with no recuperators (e.g., R113, R123, R141b) are less expensive
Restriction on condensation pressure lifted

More fluids no longer require recuperation

Cycle type
- Subcritical: Hexane, isohexane, heptane, octane, nonane, decane, MD2M, benzene, toluene
- Transcritical: Hexane, isohexane, heptane, octane, nonane, decane, D4, benzene, toluene

Fluids with $\theta_{\text{recup}} = 0$
- D4 (0.68), D5 (0.90), MM (1.00), MDM (1.00)

Fluids with $\theta_{\text{recup}} \neq 0$
- D5 (0.70), MM (1.00), MDM (1.00), MD2M (1.00)

Considerable improvements in power output, up to 200% in some cases

$P_{\text{cond}} \geq 1\text{ atm}^{***}$

$0.002\text{ bar} \leq P_{\text{cond}} \geq 0.76\text{ bar}$
Conclusions

• Case study:
  • Waste-heat recovery from a high-temperature flue-gas stream
  • Over 30 working-fluids; properties from Refprop
  • Objective of maximum power output

• Optimal reduced evaporation pressure (not sub-atmospheric):
  • Transcritical cycles (pentane, R113/123, benzene/toluene)
  • Optimal pressure ratio: 4 – 5 for the refrigerants and light hydrocarbons
  • Optimal pressure ratio: 1 – 2 for heavier hydrocarbons and siloxanes

• Recuperators are required in subcritical systems due to limits on evaporation pressure; transcritical systems rely less on recuperators

• Systems without limits on evaporation/condensation pressure/temperature produce higher power outputs and rely less on the use of recuperators
Thank you for listening.

Oyeniyi A. Oyewunmi, Steven Lecompte, Michel De Paepe, and Christos N. Markides

Contact: o.oyewunmi@imperial.ac.uk; www.imperial.ac.uk/cep

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South Kensington Campus, London, SW7 2AZ, UK