Imperial College London

IV International Seminar on ORC Power Systems
13 – 15th September, 2017, Milan, Italy

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

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

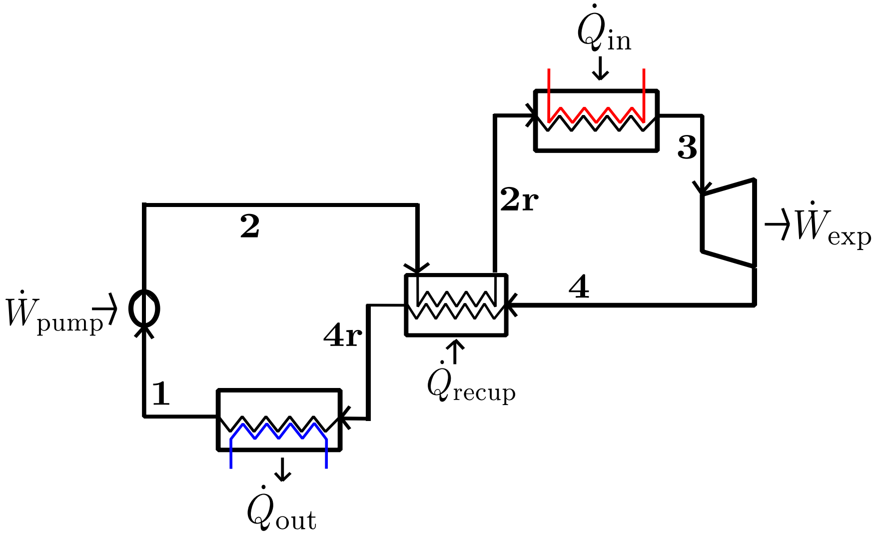
Clean Energy Processes (CEP) Laboratory
Department of Chemical Engineering
Imperial College London
South Kensington Campus, London, SW7 2AZ, UK

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

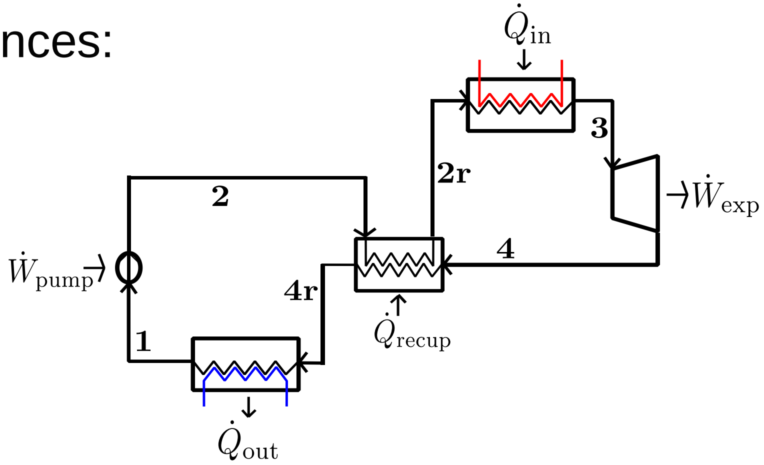
ORC system configurations/architectures

- Subcritical systems
- Transcritical systems
- Trilateral, partial evaporative, and other systems
- Recuperative ORC systems?



Model and algorithm – thermodynamic model

- Energy balances:



- Assumptions:

$\eta_{s,\text{exp}} = 75\%$
$\eta_{s,\text{pump}} = 85\%$
$\Delta T_{\text{min}} = 10\ ^\circ\text{C}$

- Recuperator:

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

$\theta_{\text{recup}} \cong 0 \rightarrow\rightarrow$ No recuperation, $T_4 = T_{4\text{r}}$, $T_2 = T_{2\text{r}}$

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

Model and algorithm – costing model

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

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

$$C_p^0 = F10^{(Z_1+Z_2\log X+Z_3\log(X)^2)}$$

X	the sizing attribute (power, heat-transfer area etc.)
$F,\ Z_n$	correlation coefficients

- 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:

$$\textbf{maximize } \dot{\boldsymbol{W}}_{\textbf{net}}$$

$$\text{subject to: } \Delta T_i \geq \Delta T_{\text{min}}(10\ ^\circ\text{C}) \ \ \forall\, i$$

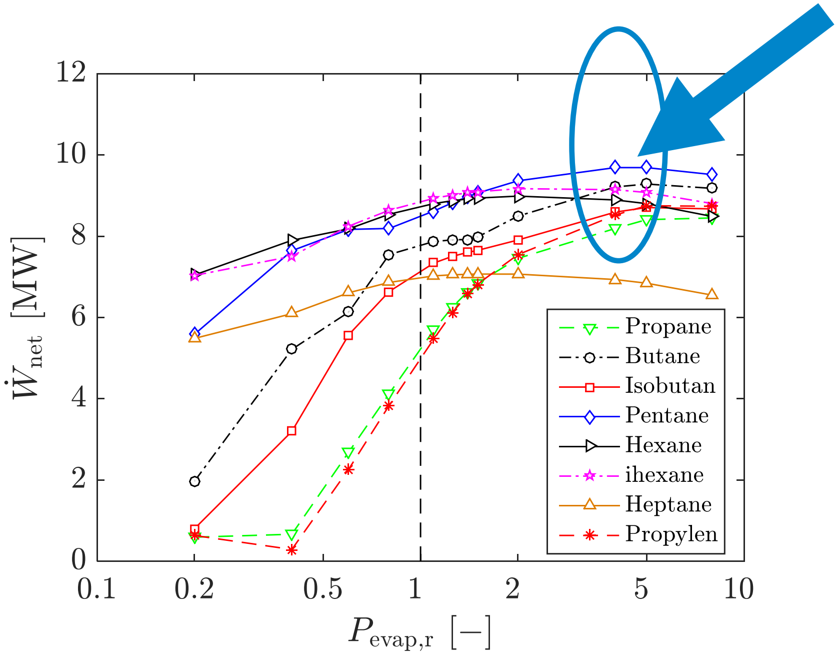
$$T_4 \geq T_{\text{dew}}(P_{\text{cond}})$$

$$0 \leq \theta_{\text{SH}}, \theta_{\text{recup}} \leq 1$$

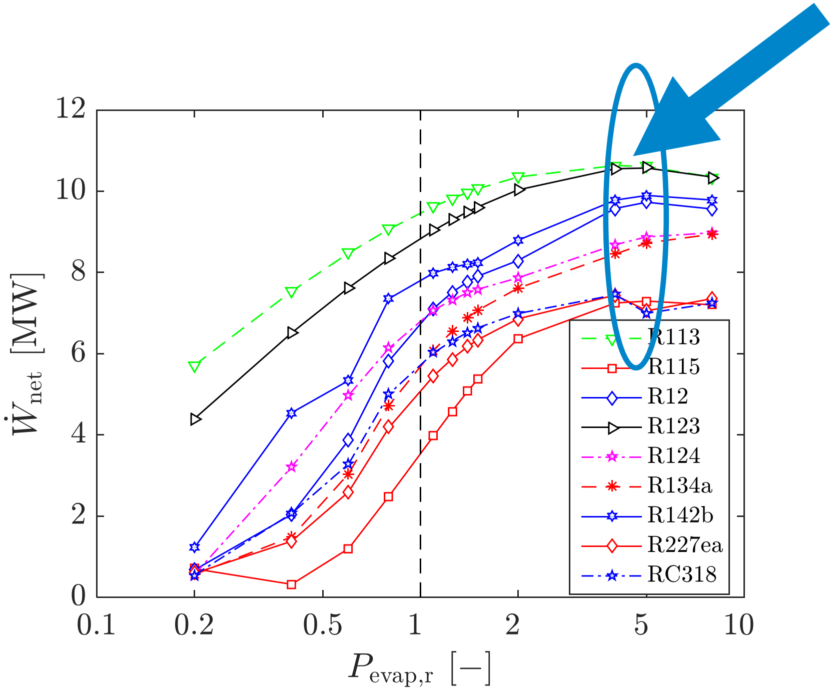
$$P_{\text{evap}} \leq 0.95 P_{\text{crit}} \text{ or } P_{\text{evap}} \geq 1.05 P_{\text{crit}}$$

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

Results: Effect of evaporation pressure (1/2)

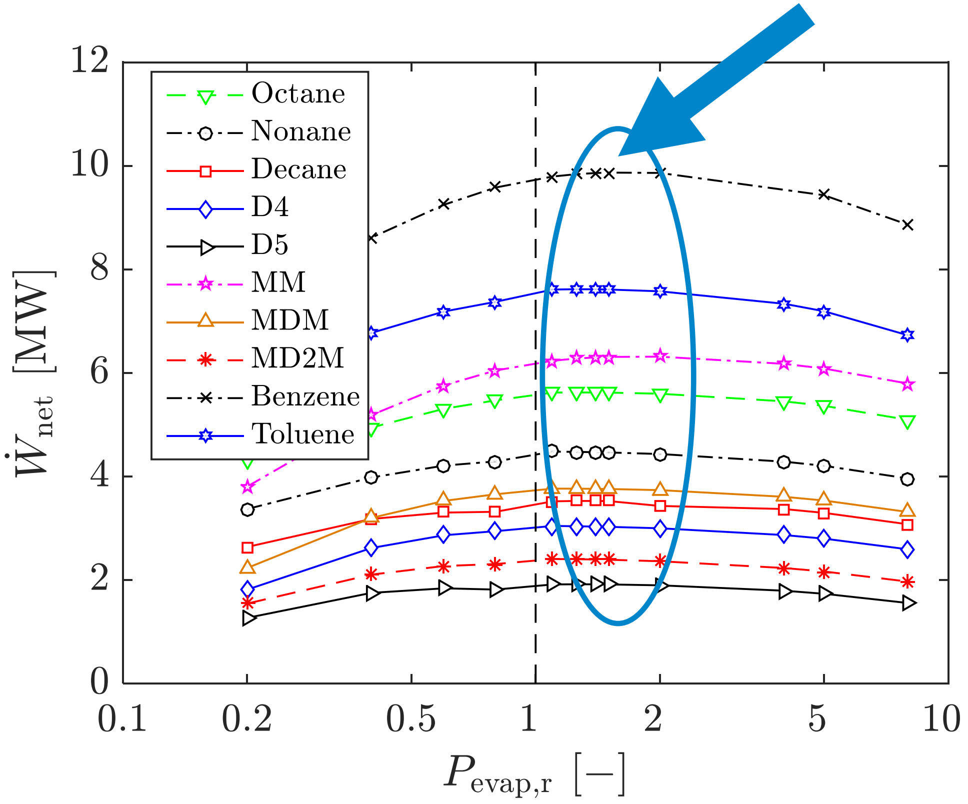


Light hydrocarbons



Refrigerants

Results: Effect of evaporation pressure (2/2)

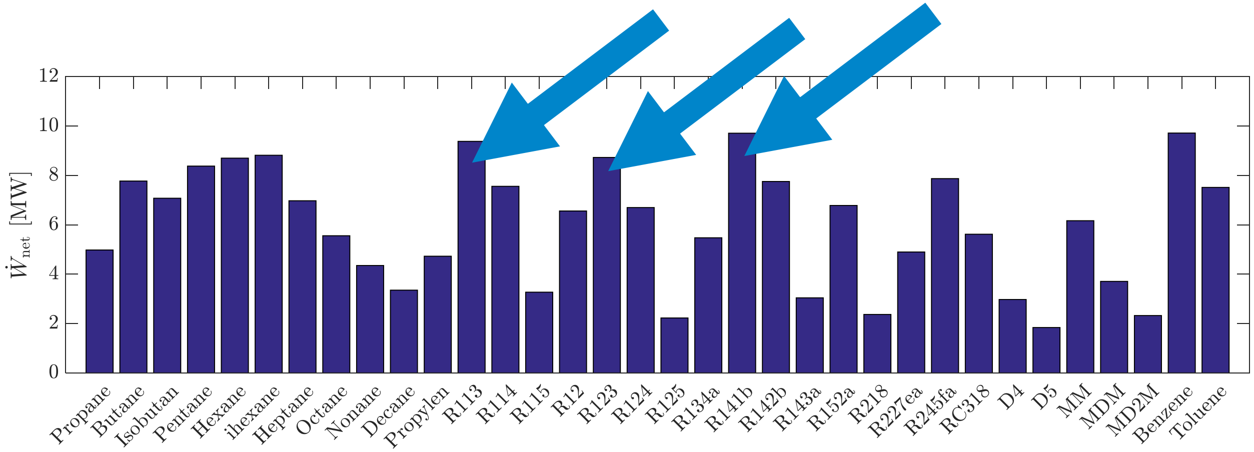


Condensation at atmospheric pressure

$$P_{\mathrm{cond}} = 1\ \mathrm{atm}$$

Heavy working fluids

Results: Recuperators in subcritical cycles



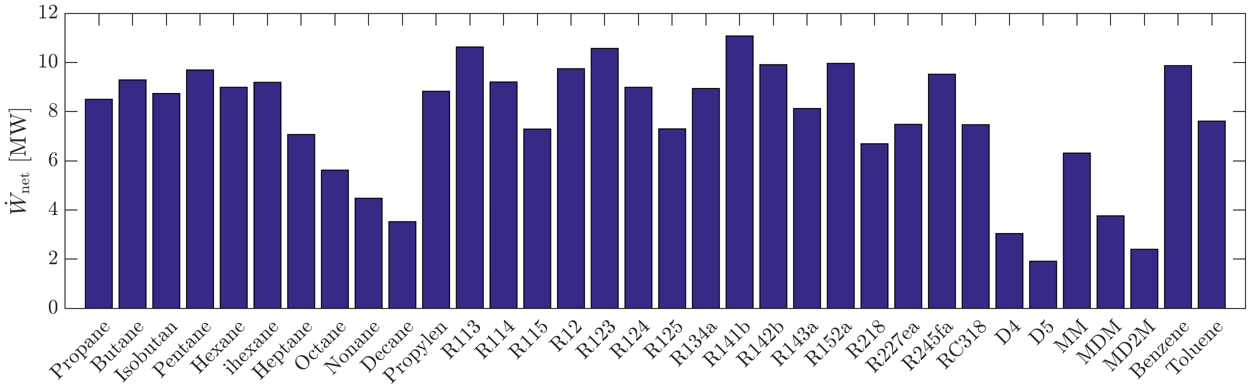
$$P_{\text{evap}} = 0.95 P_{\text{crit}}$$

Fluids with $\theta_{\text{recup}} = 0$	Fluids with $0 < \theta_{\text{recup}} < 1$	Fluids with $\theta_{\text{recup}} = 1$
Pentane, R113, R123, R141b	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)	Butane, isobutane, hexane, isohexane, heptane, octane, nonane, R114, R124, R142b, R152a, R227ea, R245fa, RC318, D4, D5, MM, MDM, MD2M

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



$\cancel{P_{\text{evap}} \le 0.95 P_{\text{crit}}}$

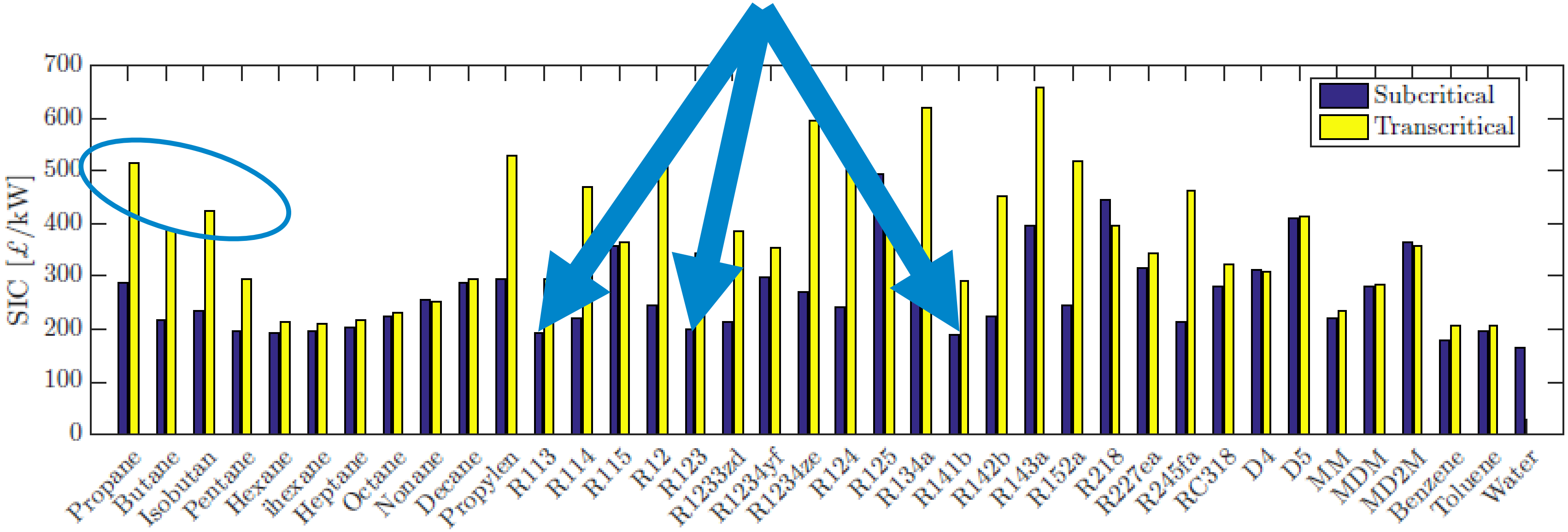
$P_{\text{evap}} \ge 1.05 P_{\text{crit}}$

Fluids with $\theta_{\text{recup}} = 0$	Fluids with $0 < \theta_{\text{recup}} < 1$	Fluids with $\theta_{\text{recup}} = 1$
Propane, butane, isobutane, pentane, propylene, R113, R114, R12, R123, R124, R134a, R141b, R142b, R143a, R152a, R245fa	Isohexane (0.80), benzene (0.01), toluene (0.06)	Hexane, heptane, octane, nonane, decane, R115, R125, R218, R227ea, RC318, D4, D5, MM, MDM, MD2M

- More fluids (16) no longer require recuperator

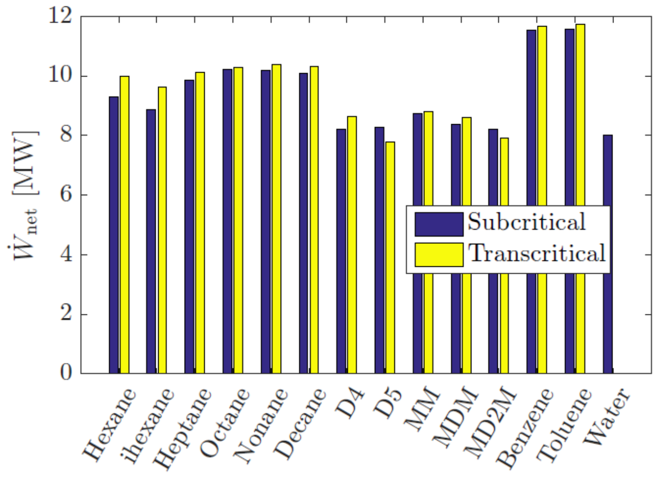
- A few refrigerants
- Heavy fluids due to condensation limit at 1 atm

Results: Costs of sub- and transcritical systems



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

Results: Relaxing condenser boundary condition



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

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

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

Cycle type	Fluids with $\theta_{\text{recup}} = 0$	Fluids with $\theta_{\text{recup}} \neq 0$
Subcritical	Hexane, isohexane, heptane, octane, nonane, decane, MD2M, benzene, toluene	D4 (0.68), D5 (0.90), MM (1.00), MDM (1.00)
Transcritical	Hexane, isohexane, heptane, octane, nonane, decane, D4, benzene, toluene	D5 (0.70), MM (1.00), MDM (1.00), MD2M (1.00)

- Restriction on condensation pressure lifted
- More fluids no longer require recuperation

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

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