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An Assessment of Working-Fluid Mixtures in ORCs for Waste Heat Recovery using SAFT-VR

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NB: Some information from the original presentation has been omitted for confidentiality reasons.

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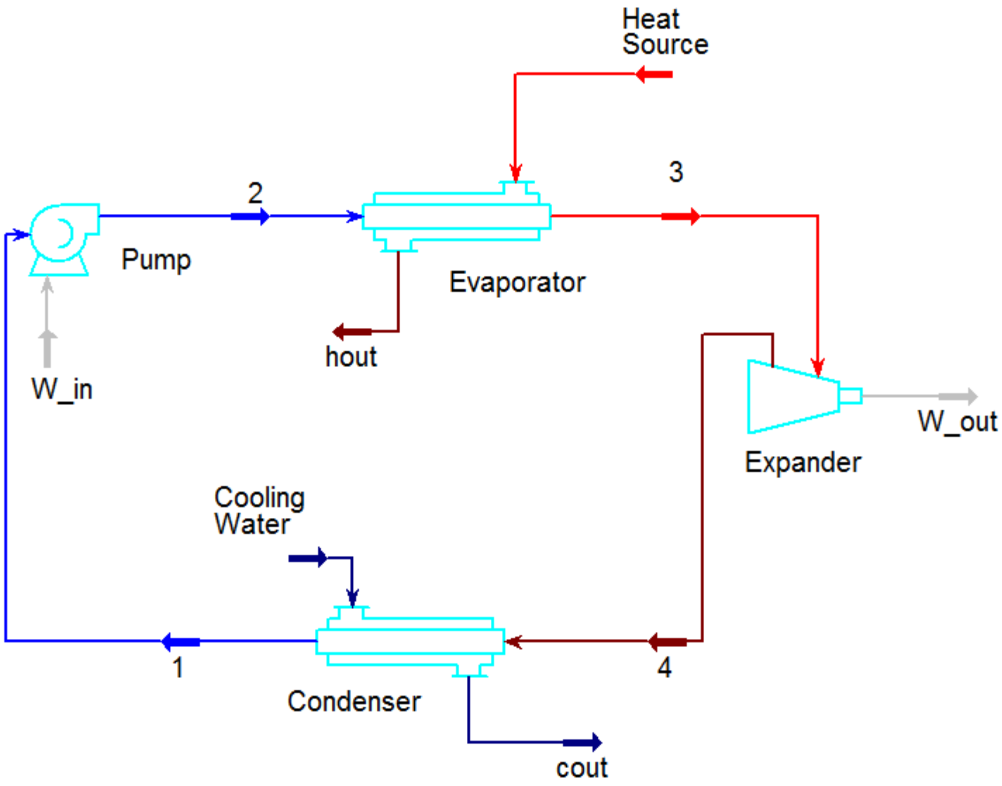
Aims & Objectives

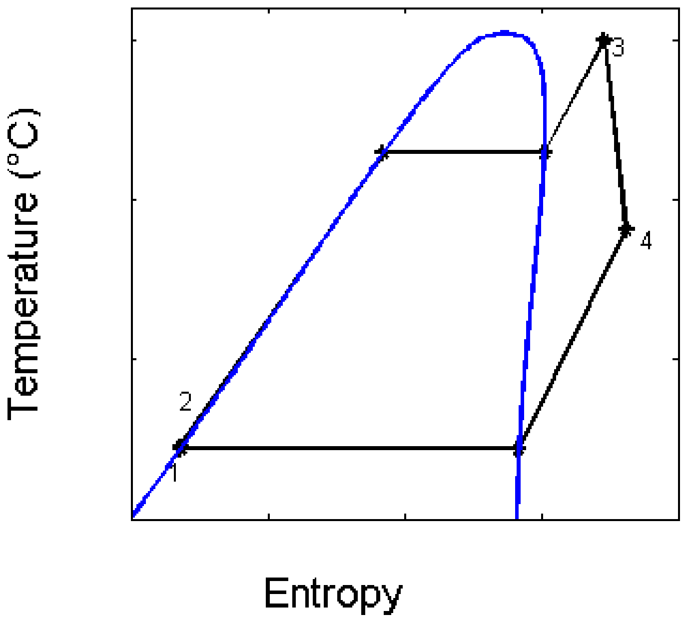
To evaluate the advantages of different working fluid mixtures for optimal organic Rankine cycles by:

1. Calculating relevant fluid properties of a wide range of working fluid mixtures with SAFT-VR
2. Linking SAFT-VR with a thermodynamic model of an ORC and calculating performance parameters (efficiency, power output, costs)

The Organic Rankine Cycle (ORC)



ORC schematic



ORC with butane on a *T*-*s* plot

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ORC Model

Cycle definition:

Pump ($1 \rightarrow 2$)

- $\dot{W}_{\text{pump}} = \dot{m}_{\text{wf}}(h_2 - h_1)$

Evaporator ($2 \rightarrow 3$)

- $Q_{\text{in}} = \dot{m}_{\text{hs}} c_{\text{p,hs}} \left(T_{\text{hs,in}} - T_{\text{hs,out}}\right)$
- $Q_{\text{in}} = \dot{m}_{\text{wf}}(h_3 - h_2)$

Expander ($3 \rightarrow 4$)

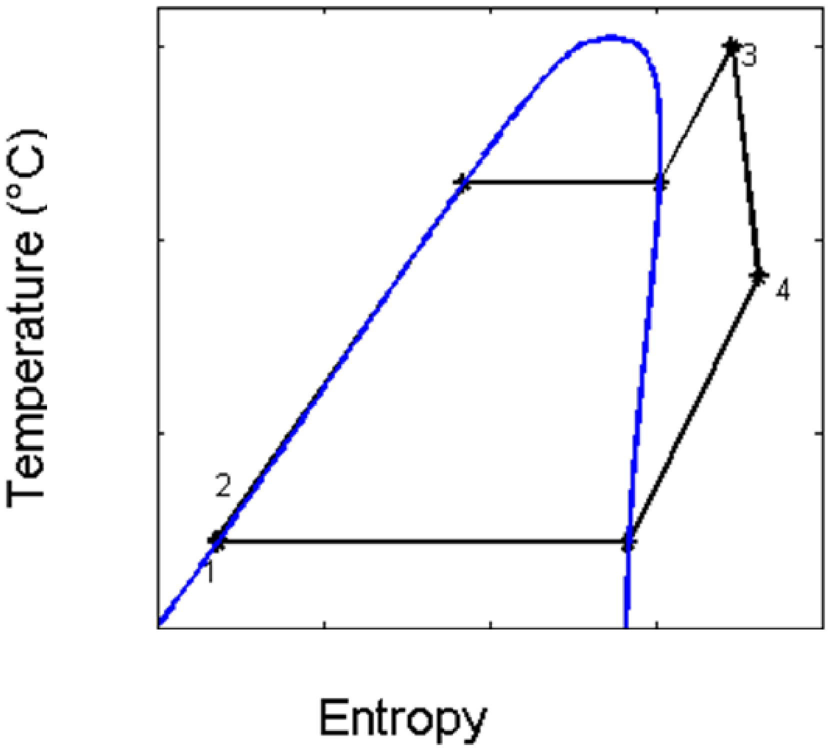
- $\dot{W}_{\text{exp}} = \dot{m}_{\text{wf}}(h_3 - h_4)$

Condenser ($4 \rightarrow 1$)

- $Q_{\text{out}} = \dot{m}_{\text{cs}} c_{\text{p,cs}} \left(-T_{\text{cs,in}} + T_{\text{cs,out}}\right)$
- $Q_{\text{out}} = \dot{m}_{\text{wf}}(h_4 - h_1)$

$$\eta_{\text{th}} = \frac{\dot{W}_{\text{exp}} - \dot{W}_{\text{pump}}}{Q_{\text{in}}}$$

Case considered: Heat source – Flue gas from a refinery preheater (200 °C, 560 kg/s)



Component Cost Calculation

Heat exchangers – **C-value method**

- $\text{Cost} = C\frac{Q}{\Delta T_{Lm}} = C \times (UA)$

Pumps and Expanders – **Market survey**

Component costs ≈ 0.45 - 0.7 x overall costs for typical ORCs for waste heat recovery (Koehler 2005, Lukawski 2009, Bejan et al. 1996)

NB: Costs shown in this work are not TOTAL system costs; but the added costs of the basic ORC system components (i.e. heat exchangers, pumps and expanders)

Model Parameters and Variables

Inputs:

- Variable
  - Expander inlet temperature T_3
  - Evaporation pressure P_{23}
  - Mass flow rate $\dot{m}$
  - Working fluid mixing ratio
- Fixed parameters
  - Pinch temperature 10 °C
  - Heat source T = 200 °C
- Fluid properties
  - Pure properties from NIST database
  - Mixture properties from SAFT-VR EoS

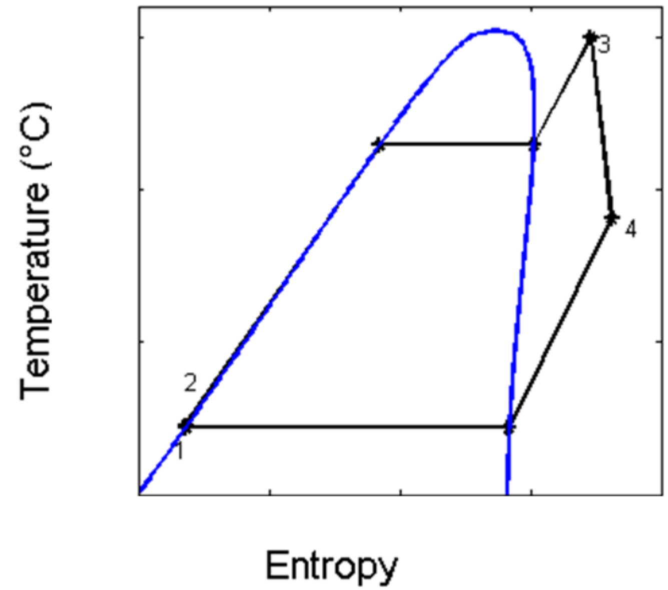
Outputs:

Power output ($\dot{W}_{\mathrm{exp}}$)

Thermal efficiency (η_{th})

Capital cost (£)

Cost per unit power (£/kW)



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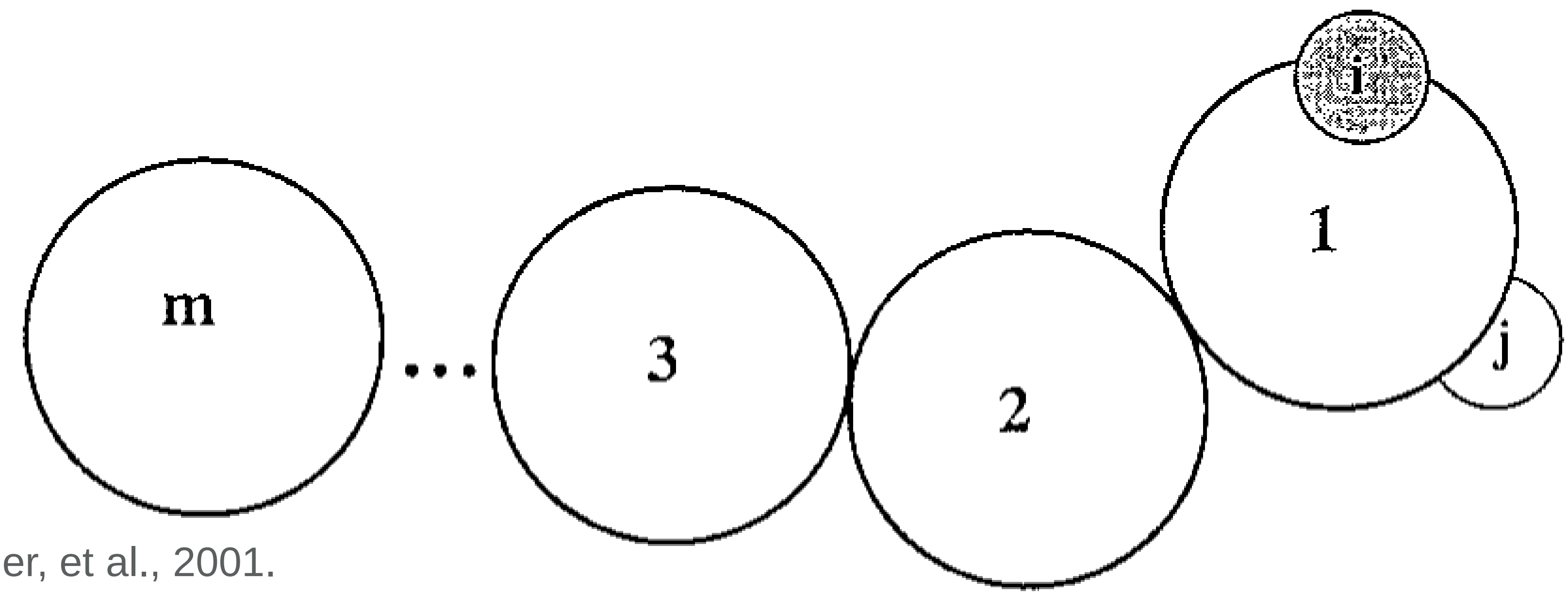
SAFT-VR for Mixture Fluid Properties

- SAFT-VR divides molecules into building blocks or spheres
- Each sphere can have four different effects:

$$A = A^{\text{ideal}} + A^{\text{mono}} + A^{\text{chain}} + A^{\text{assoc.}}$$



Müller, et al., 2001.

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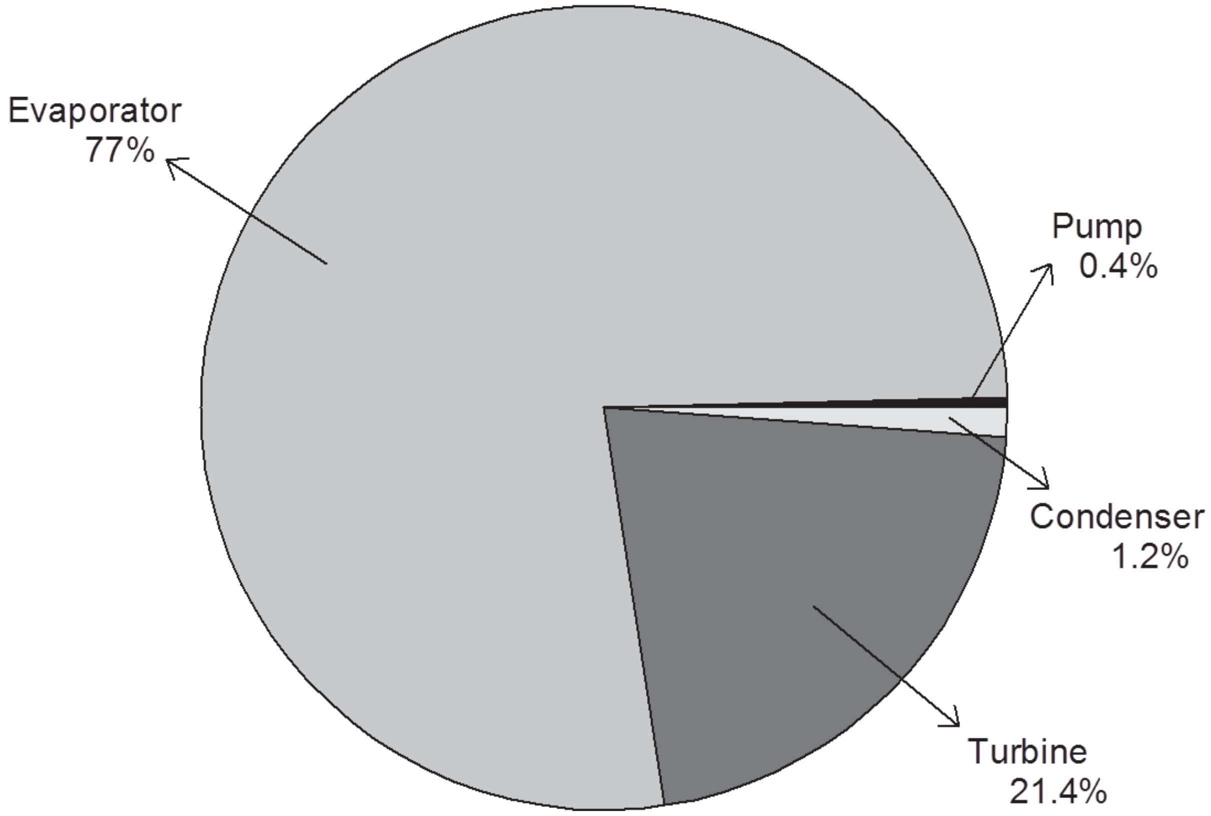
Why Working Fluid Mixtures - Exergy Loss in a typical ORC



- Main source of **exergy destruction** in ORC is the heat exchanger of the **evaporator**
- Exergetic losses in evaporator must be reduced

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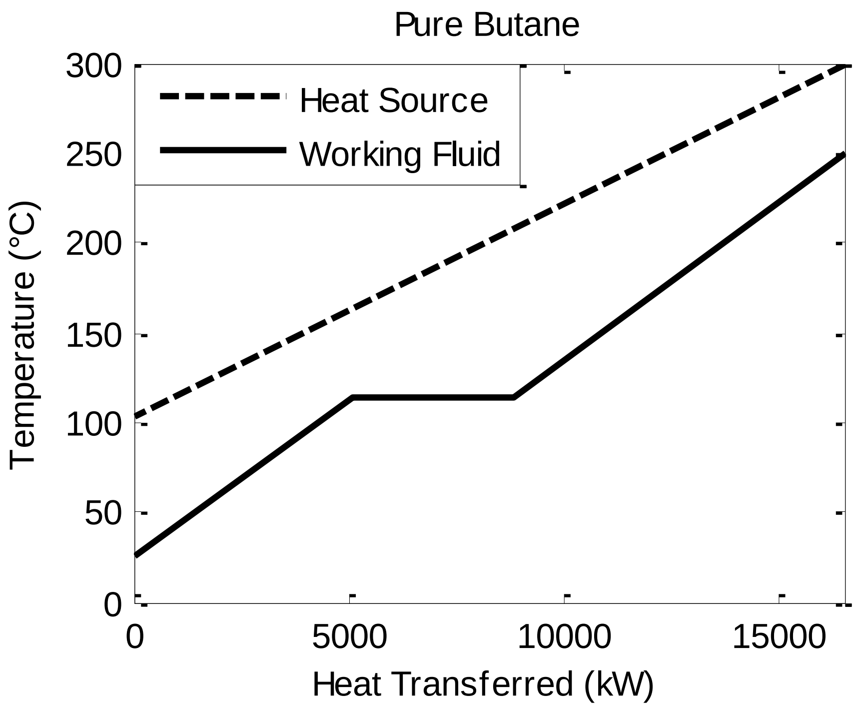
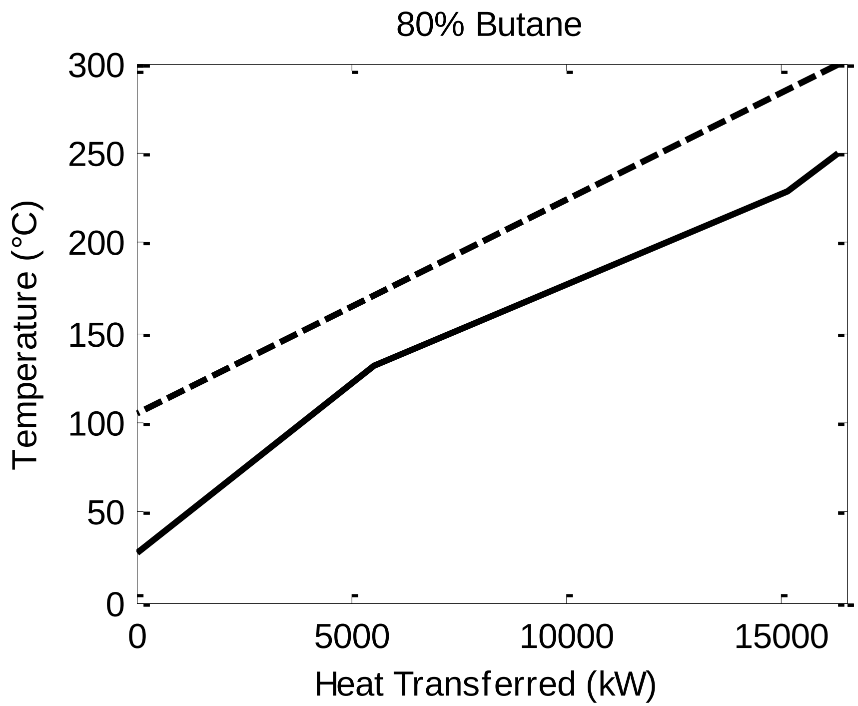
Pure Working Fluids vs. Working Fluid Mixtures





- By increasing **average temperature** of heat addition

→ **Efficiency and power output** increased

- Caution: average temperature of heat rejection may also be increased which leads to efficiency losses

Perfluoroalkane (C_4F_{10} + C_5F_{12}) Mixtures

Working fluid conditions:

- 8 bar $\leq P_{23} \leq$ 20 bar
- 100 °C $\leq T_3 \leq$ 190 °C
- 1 kg/s $\leq \dot{m}_{wf} \leq$ 600 kg/s
- $0 \leq C_4F_{10} \leq 1;\ 1 \geq C_5F_{12} \geq 0$

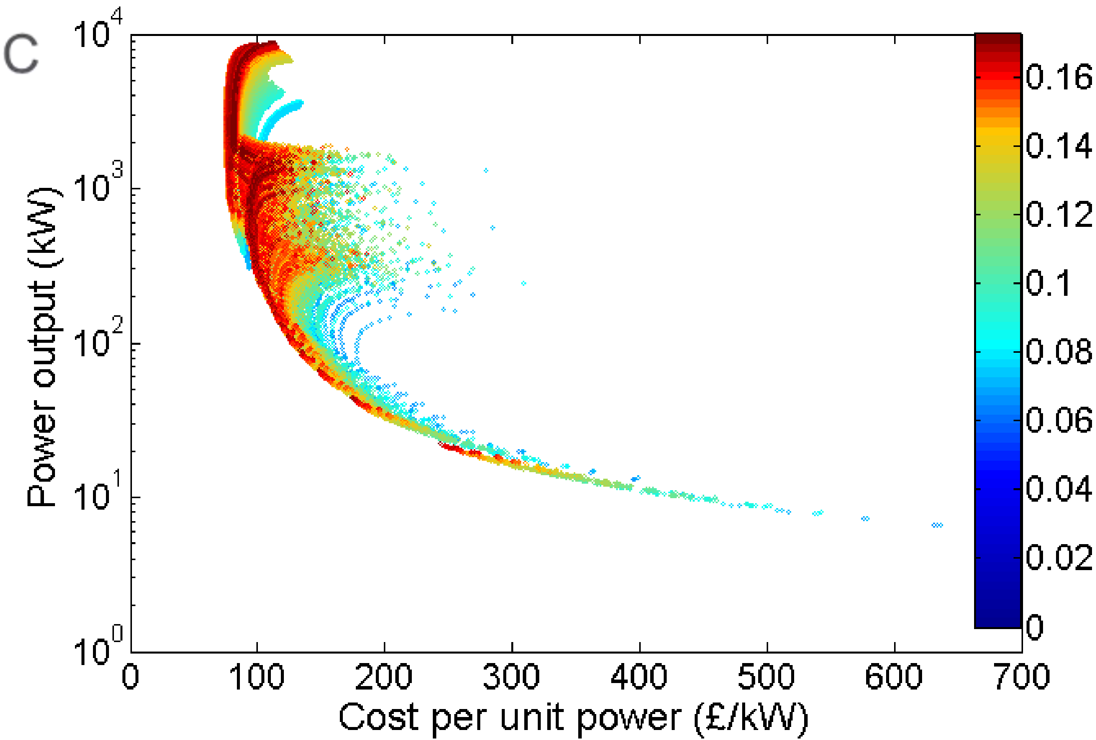
Heat Source: Flue gas at 200 °C

Power Output: 0.1 – 10 MW

Efficiency: 16 –17%

Costs: down to 100 £/kW

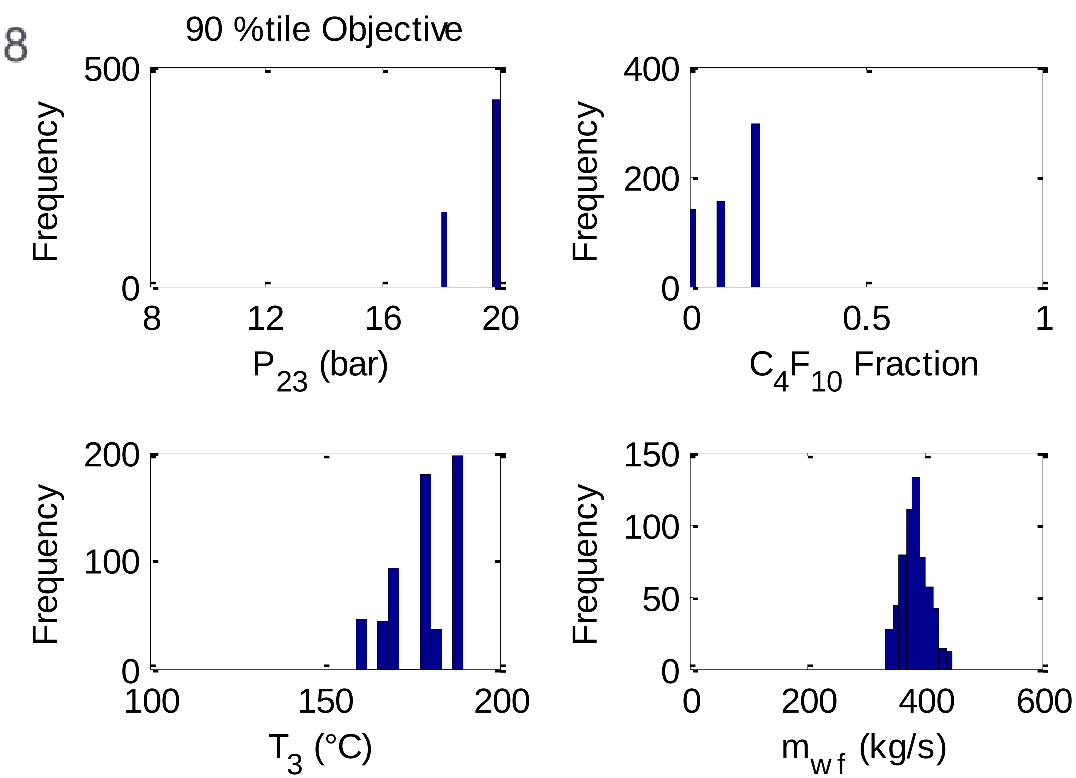
(**NB: component costs only**)



Optimal Operation Conditions for Perfluoroalkane Mixtures

Satisfactory working fluid conditions:

- 18 bar $\leq P_{23} \leq$ 20 bar
- 160 °C $\leq T_3 \leq$ 190 °C
- 300 kg/s $\leq \dot{m}_{\mathrm{wf}} \leq$ 450 kg/s
- $0 \leq C_4F_{10} \leq 0.2;\ 1 \geq C_5F_{12} \geq 0.8$



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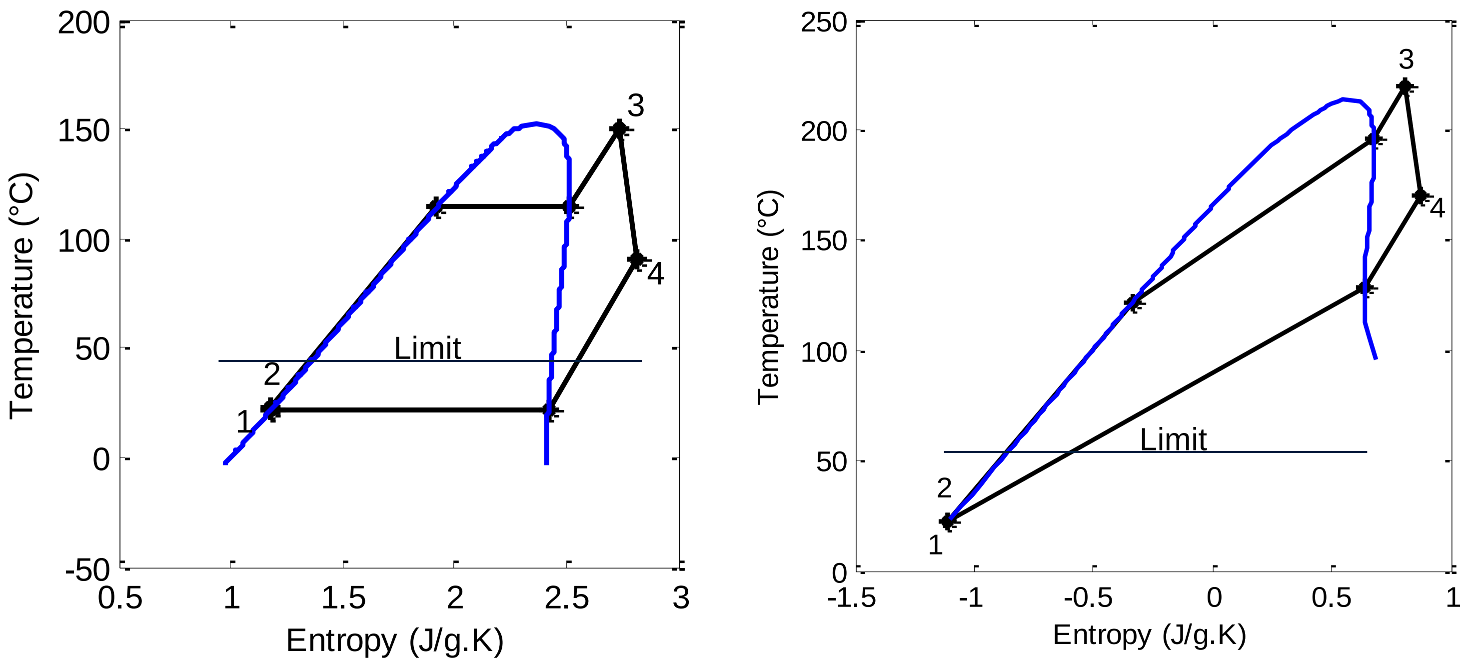
Decane + Butane Working Fluid with Regenerators

Why use regenerators?

Increased efficiencies but additional costs

Increased mass flowrates → Increased power output



T-*s* plot for: (a) Pure working fluid (b) Mixture working fluid

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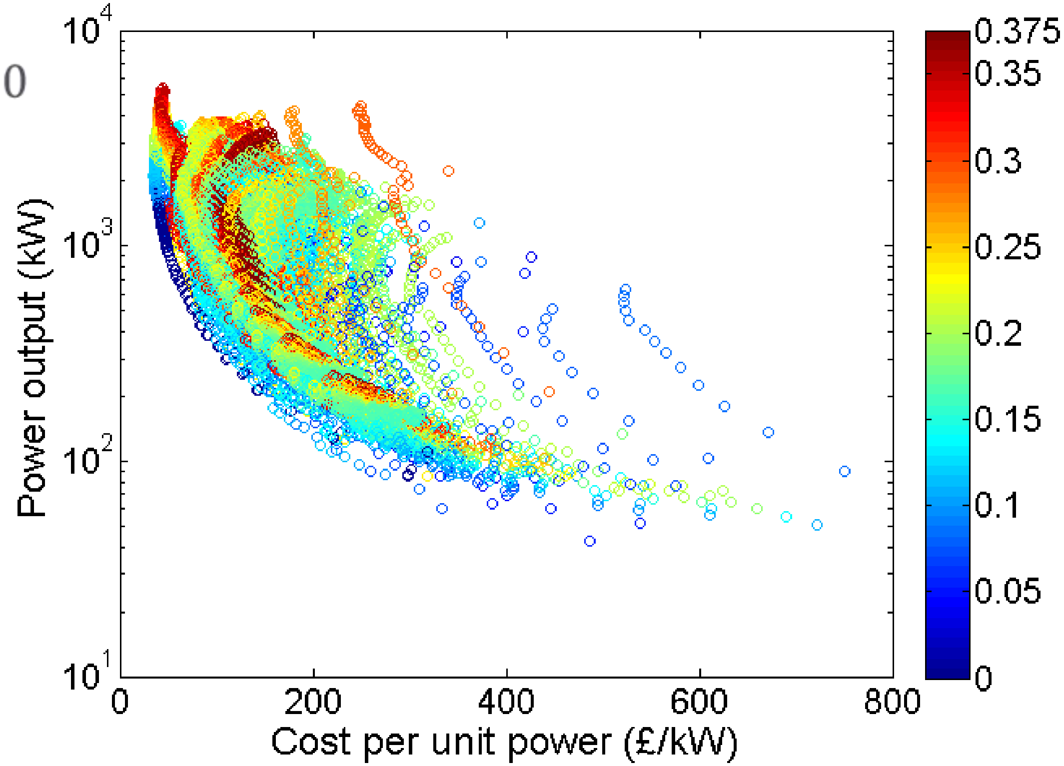
Decane + Butane Working Fluid with Regenerators

Flue gas at 330 °C

Working fluid conditions:

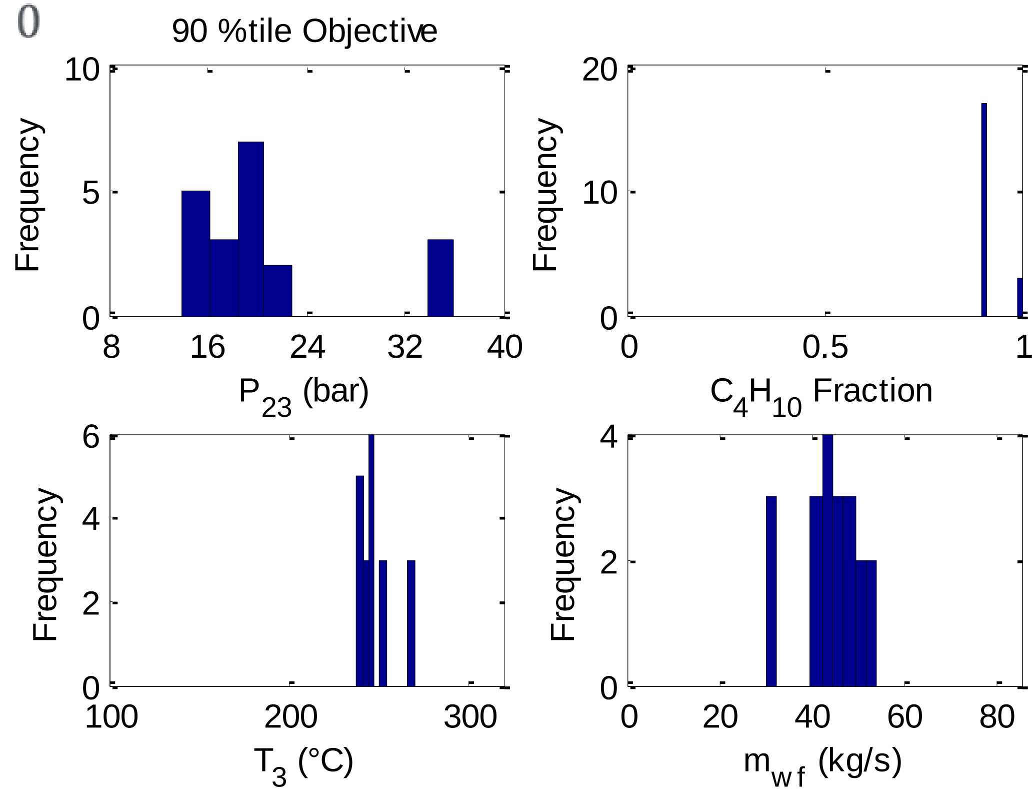
- $6 \text{ bar} \leq P_{23} \leq 40 \text{ bar}$
- $100\ ^{\circ}\text{C} \leq T_3 \leq 320\ ^{\circ}\text{C}$
- $1 \text{ kg/s} \leq \dot{m}_{wf} \leq 80 \text{ kg/s}$
- $0 \leq C_4H_{10} \leq 1;\ 1 \geq C_{10}H_{22} \geq 0$



Maximize Power Output, Efficiency and Minimize Costs per Unit Power

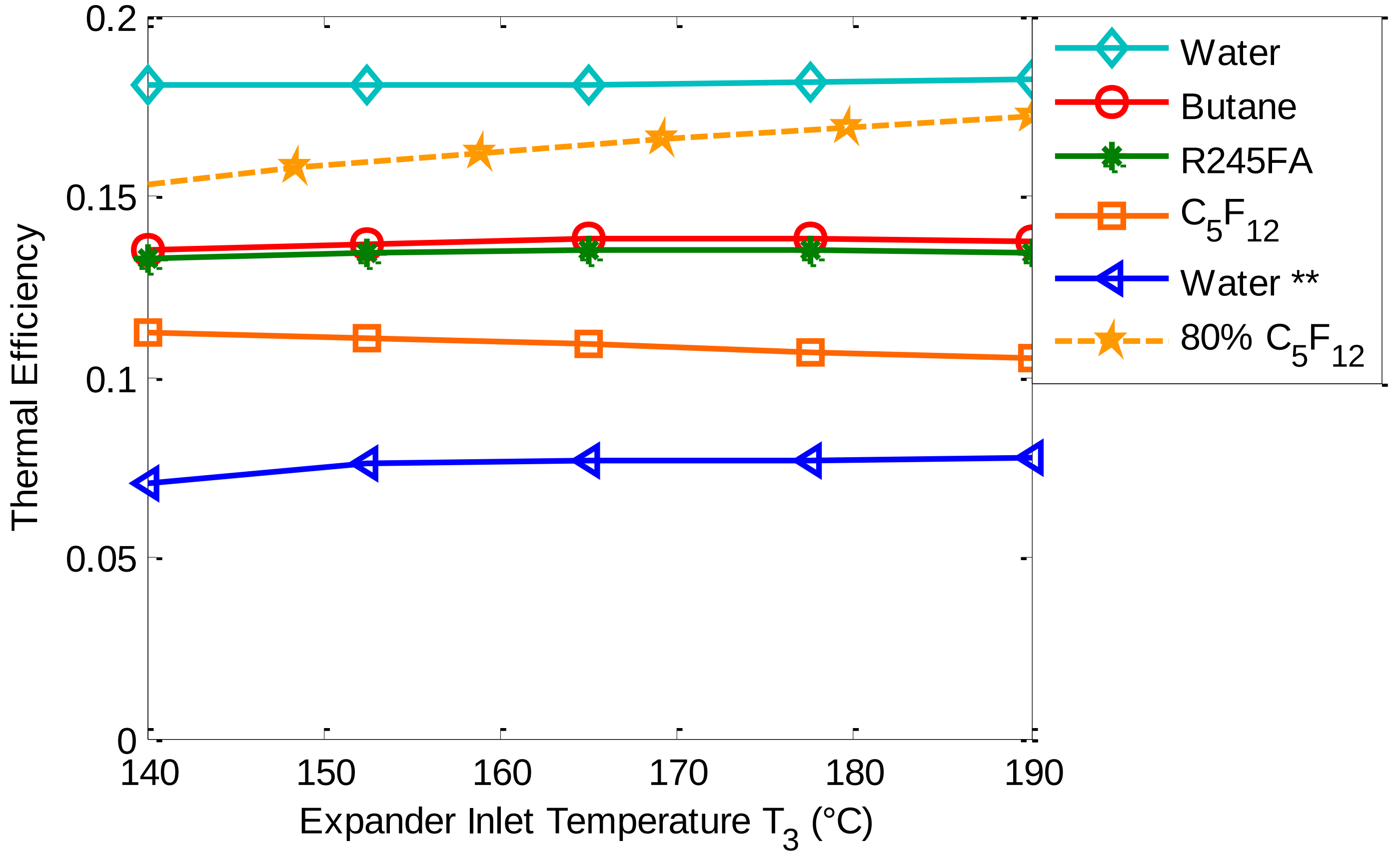
Satisfactory working fluid conditions:

- $14\ \text{bar} \leq P_{23} \leq 32\ \text{bar}$
- $250\ °\text{C} \leq T_3 \leq 280\ °\text{C}$
- $30\ \text{kg/s} \leq \dot{m}_{\text{wf}} \leq 55\ \text{kg/s}$
- $0.9 \leq C_4H_{10} \leq 1;\ 0.1 \geq C_{10}H_{22} \geq 0$



Thermal Efficiencies – Pure Working Fluids

- Organic fluids and water condensing at 30°C
- ** Water condensing at 1 bar (100°C)
- Evaporating at 140°C
- Heat source at 200°C



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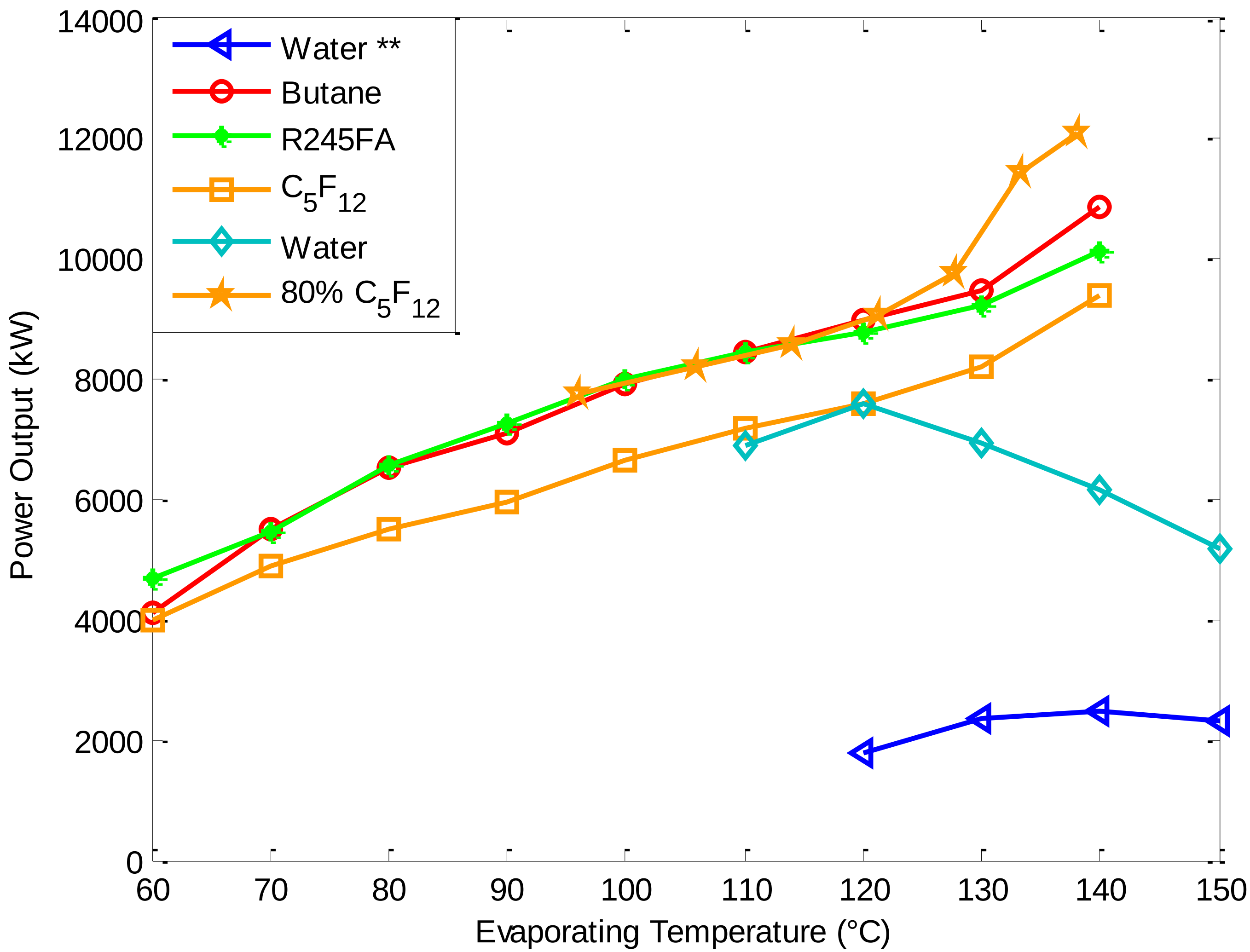
Maximum Power Output – Pure Working Fluids

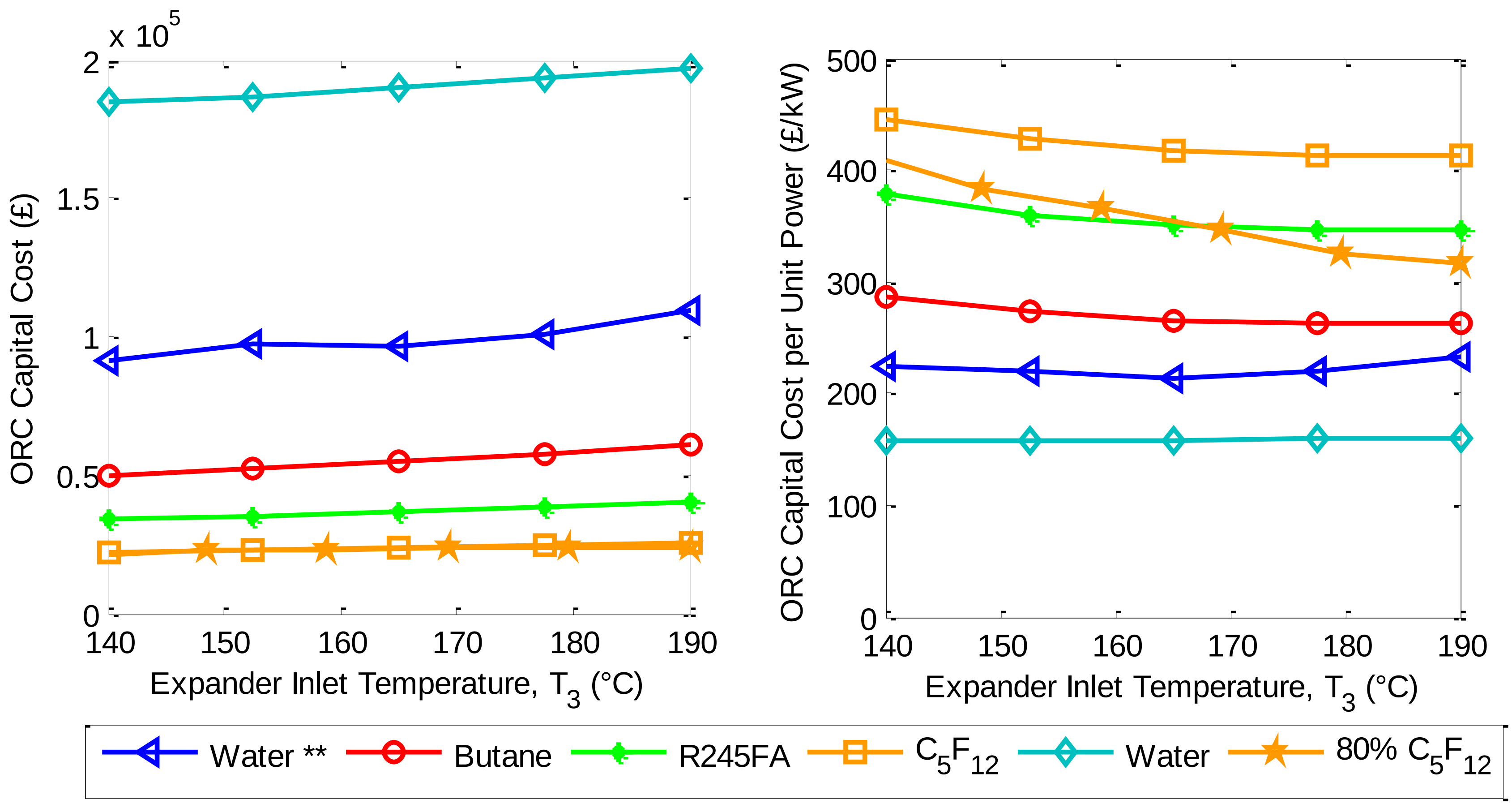


Component Cost Comparisons

$\dot{m} = 2.5 \text{ kg/s}$

Condensing at 30°C, 100°C for water

Evaporating at 140 °C and superheating to 190 °C



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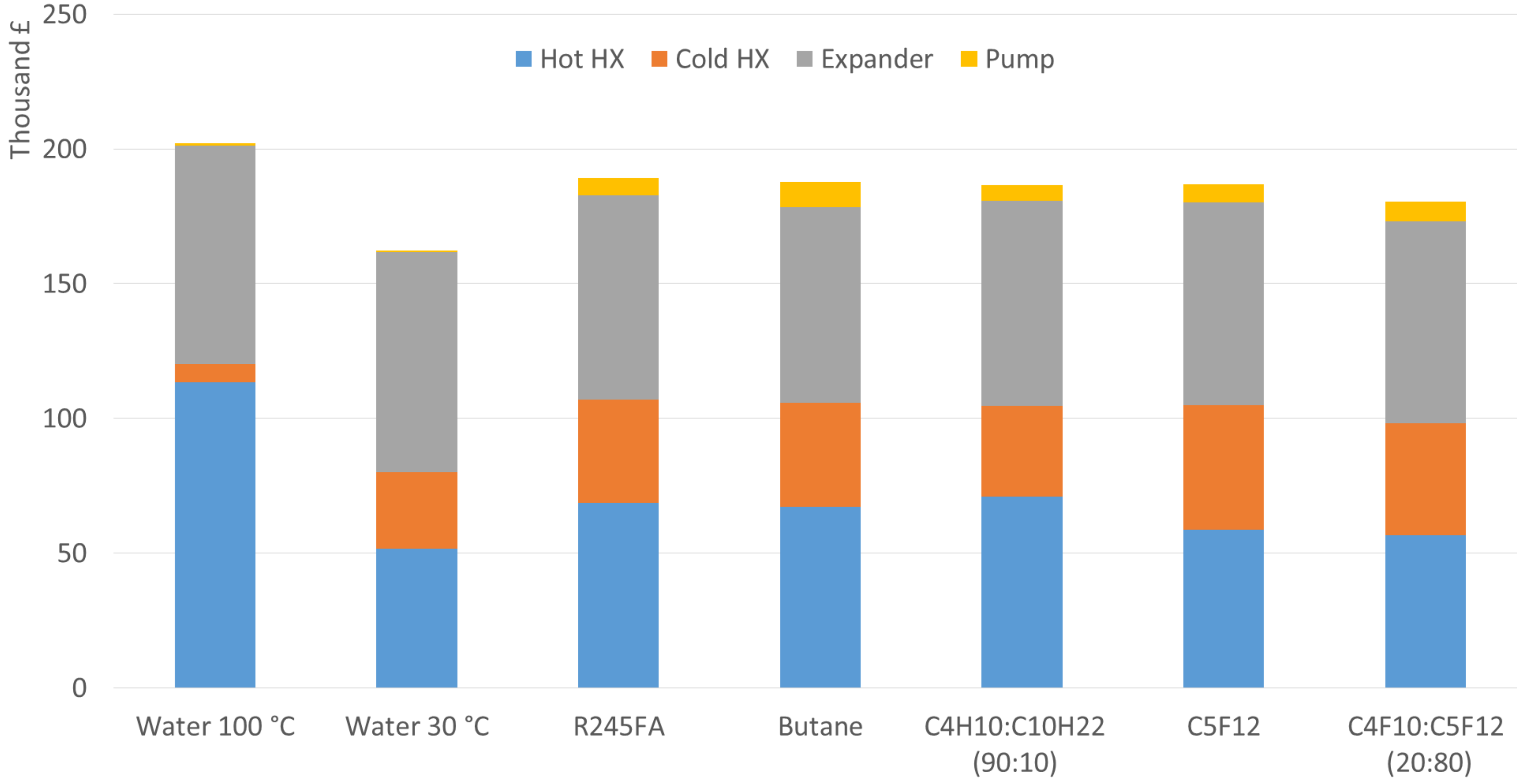
Component Cost Breakdown Comparison at 1 MW Output



Summary

- Heat source: 200 °C, 560 kg/s (modelled refinery flue gas)

Results with perfluoroalkane mixture:

- Efficiency: 16 – 17%
- Power output: 0.1 – 10 MW
- <u>Component</u> cost: <100 £/kW

Comparison perfluoroalkane mixtures, water, pure organic fluids:

- Highest efficiency: perfluroalkane mixture and water (however, condensation at 0.04 bar!)
- Highest maximum power output: perfluoroalkane mixture

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Summary and Conclusions

SAFT-VR calculates working fluid mixtures very accurately

There is no “perfect” working fluid mixture (cycle parameters + application)

Carefully selected working fluid mixtures can improve cycle performance

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Future Work

- Water mixtures (e.g. water-ethanol, etc.)
- Different homologous series (e.g. alkane + refrigerant)
- Azeotropic mixtures
- SAFT-VR for “reverse” engineering / design:
  - Define properties first and derive from that molecular structure

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Acknowledgements

Dr. Christos Markides

Dr. Andrew Haslam

Oyeniyi Oyewunmi

Daniel Eriksen

James Freeman

Haroon Siyech

This research was performed under the UNIHEAT project. The authors wish to acknowledge the Skolkovo Foundation and BP for financial support.