ORC for Geothermal Sources

An Efficient Technology?

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EASYGO ITN

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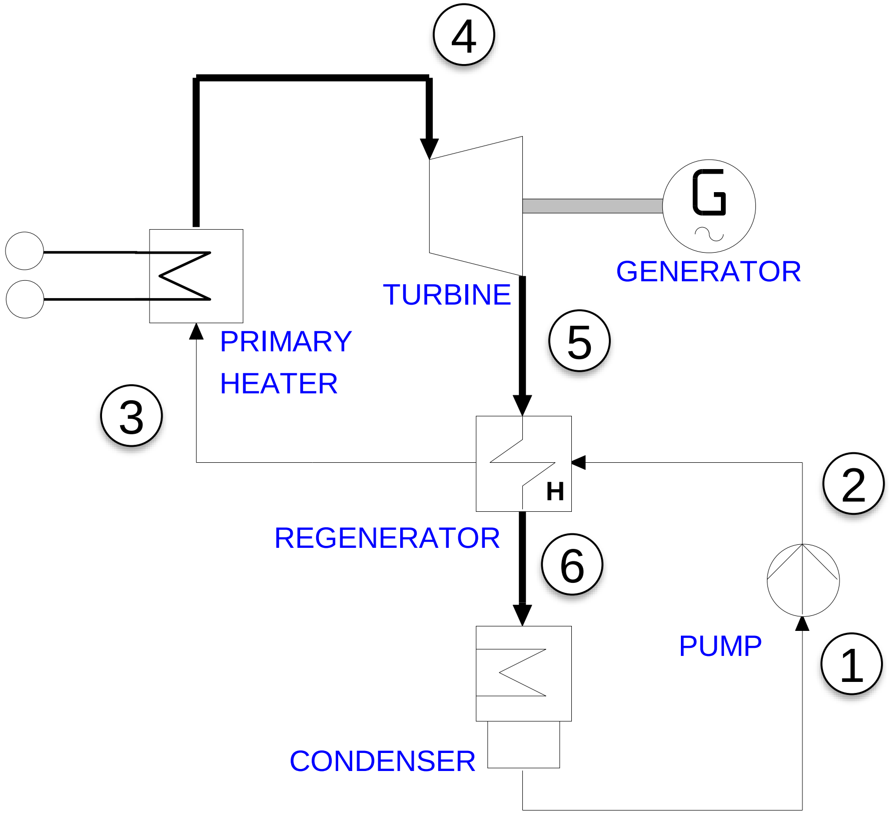
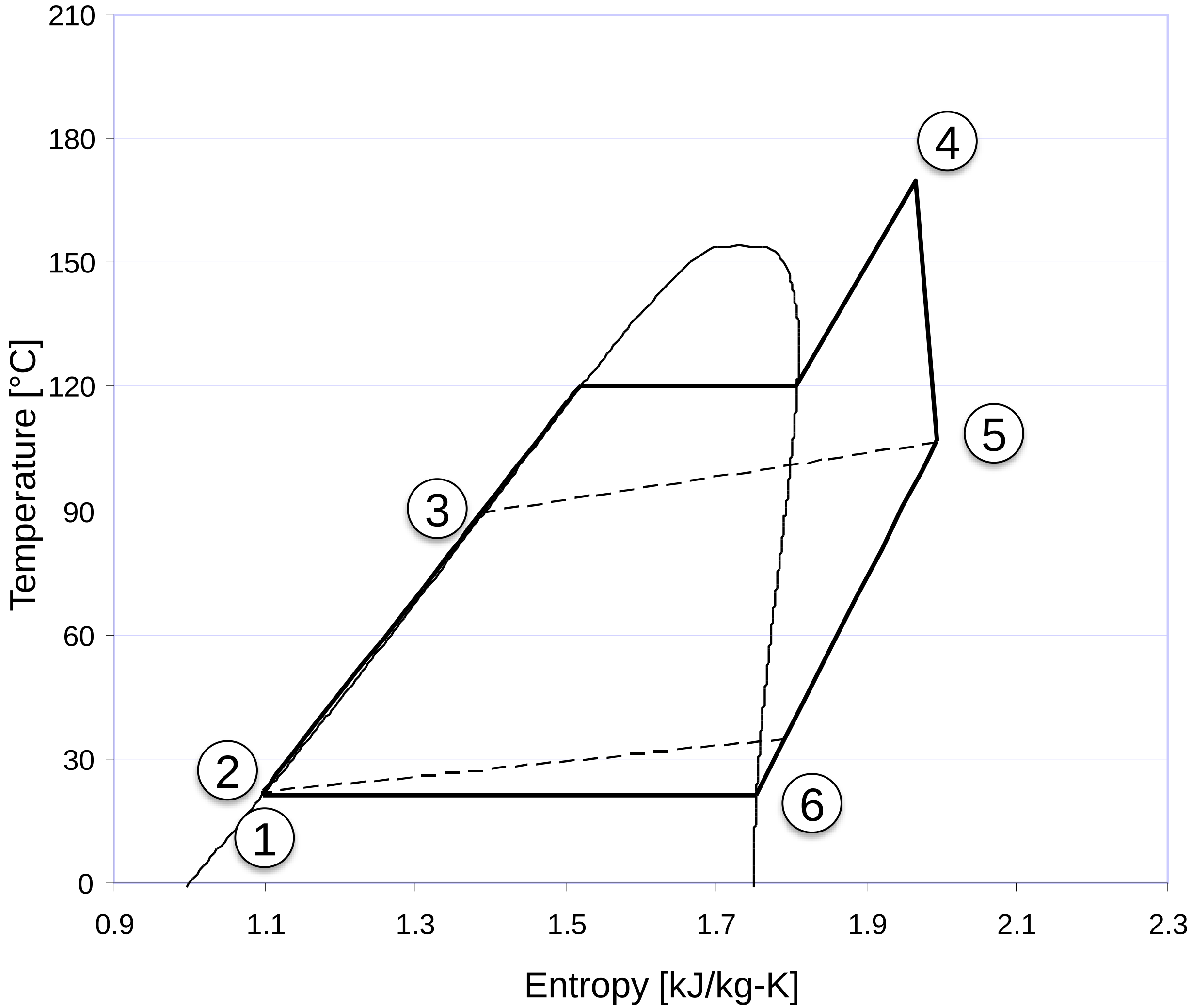
TU Delft

Propulsion & Power

ORC technology

The working principle

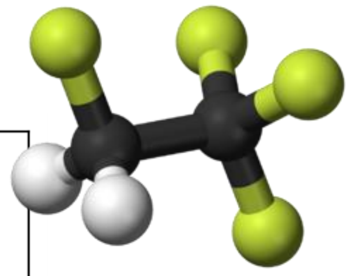


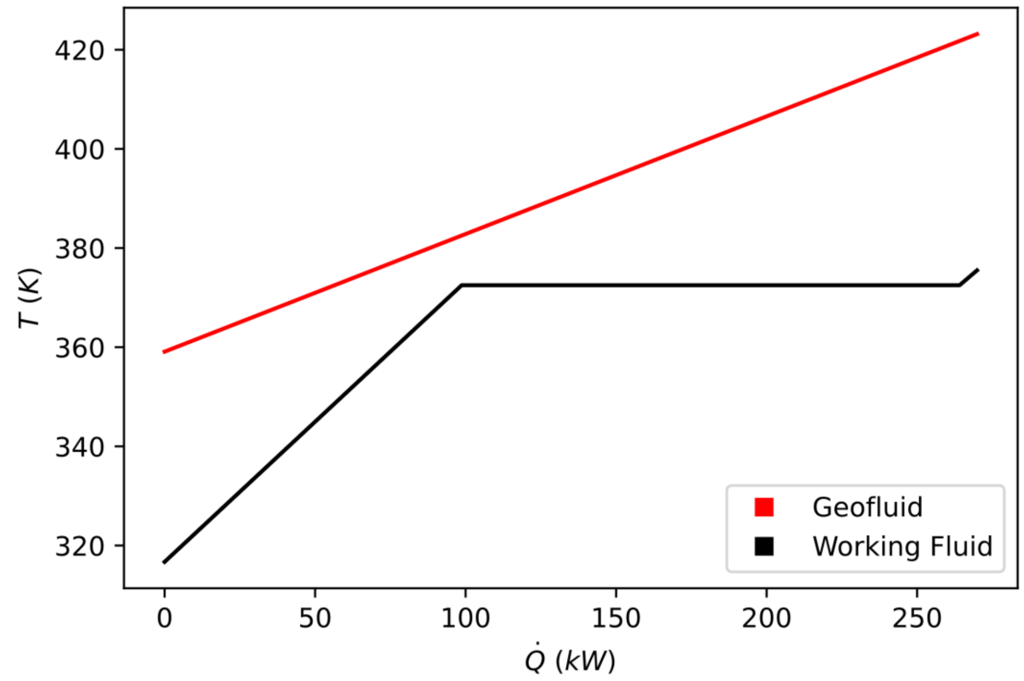


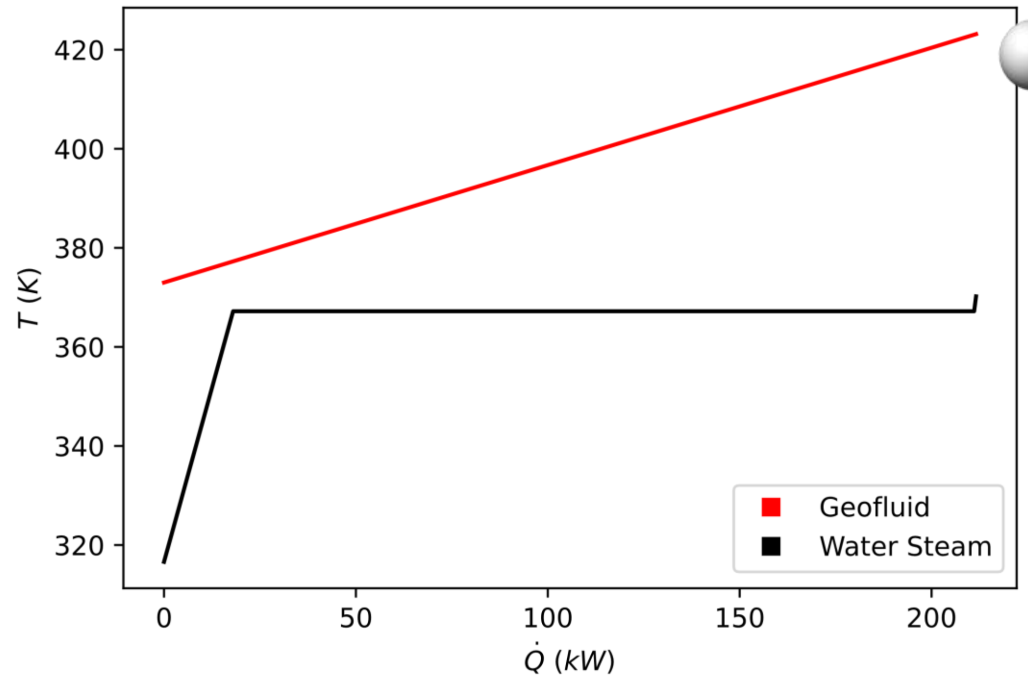
ORC tech. & geothermal applications

Why so suitable for (low-T) geothermal sources?

- Good match with *T* profile of the thermal source by **working fluid** selection







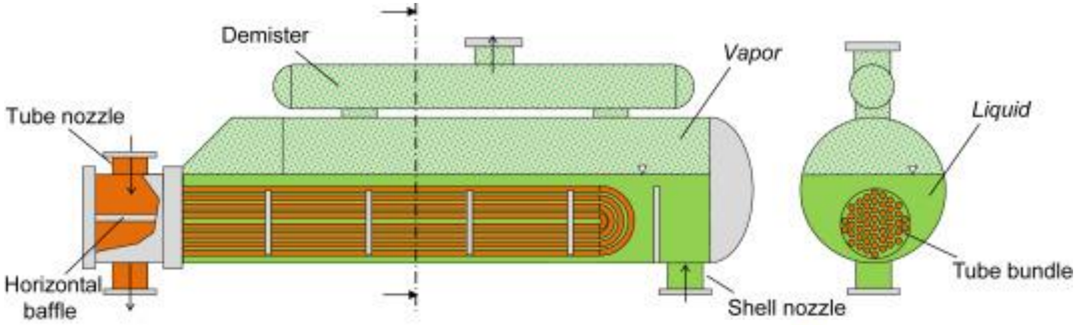
ORC tech. & geothermal applications

Why so suitable for (low-T) geothermal sources?

- Good match with *T* profile of the thermal source by **working fluid** selection
- Cycle configurations: saturated, (superheated), supercritical (at low *P*), two-pressure levels
- Simplicity (low *P*, low $\Delta h_{\text{turbine}}$, dry expansion, non-extractive regeneration)
- Higher condensing *P* than steam (@ $T_{\text{cond}} = 313\ \text{K}$, $P_{\text{steam}} = 0.07\ \text{atm}$ vs. $P_{\text{ORC}} > 1\ \text{atm}$)

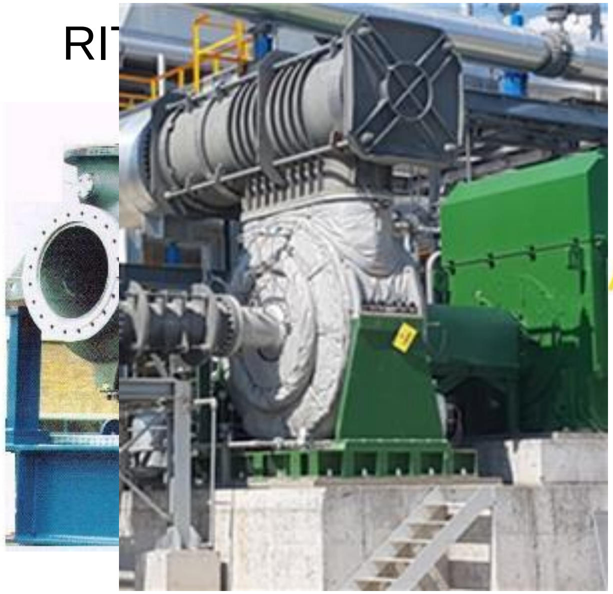
How ORC geothermal plants look like

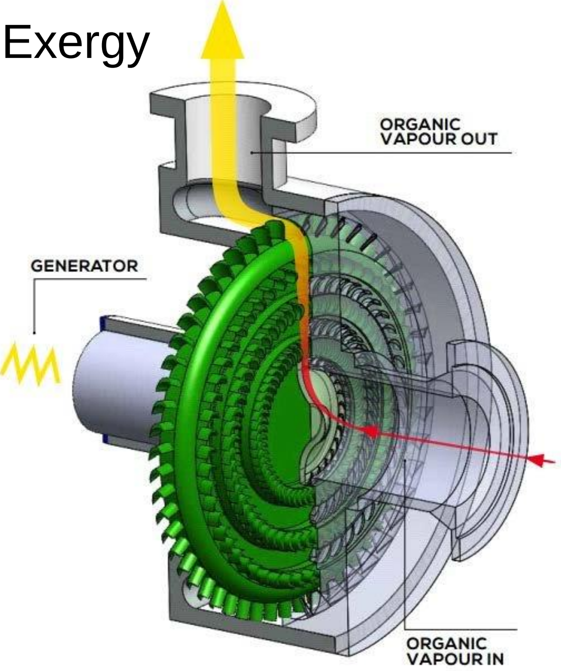
Kettle evaporator



ROT - Exergy

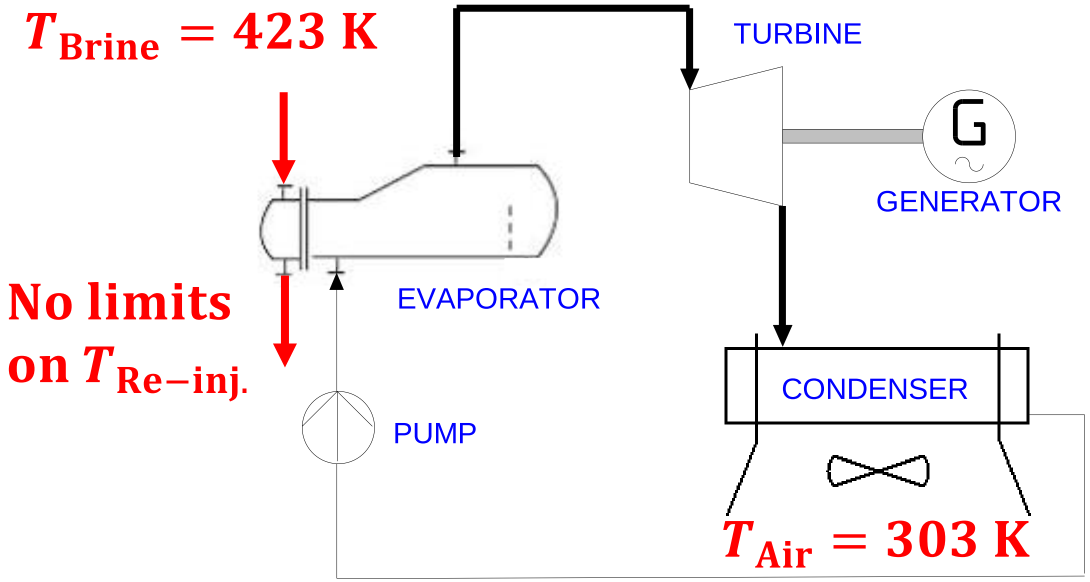
RI



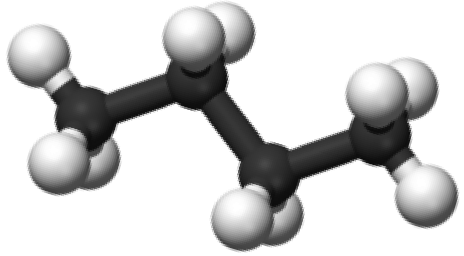


ORC plant performance – An example

Example: geothermal source with brine in liquid state @ 423 K



Butane



$$P_{\text{el}} = 25\ \text{kW/kg}_{\text{brine}}$$

$$\eta_{\text{plant}} = 4.9\%$$

ORC design variables:

$$P_{\text{evap}}, P_{\text{cond}}$$

ORC Components

- $\Delta T_{pp,HEX} = 10K$
- $\Delta T_{pp,ACC} = 5K$
- $\eta_{turbine} = 0.9$
- $\eta_{pump} = 0.8$
- $\eta_{fan} = 0.65$
- $\Delta P_{air,\,ACC} = 125\ Pa$

(Ideal) Lorentz's Cycle – The Benchmark?

$$\dot{W}_{\text{rev}} = \dot{m}_{brine}\left[(h - h_0) - T_0(s - s_0)\right] = \dot{Q}_{\text{avail.}}\left[1 - \frac{T_0}{\Delta h/\Delta s}\right]$$

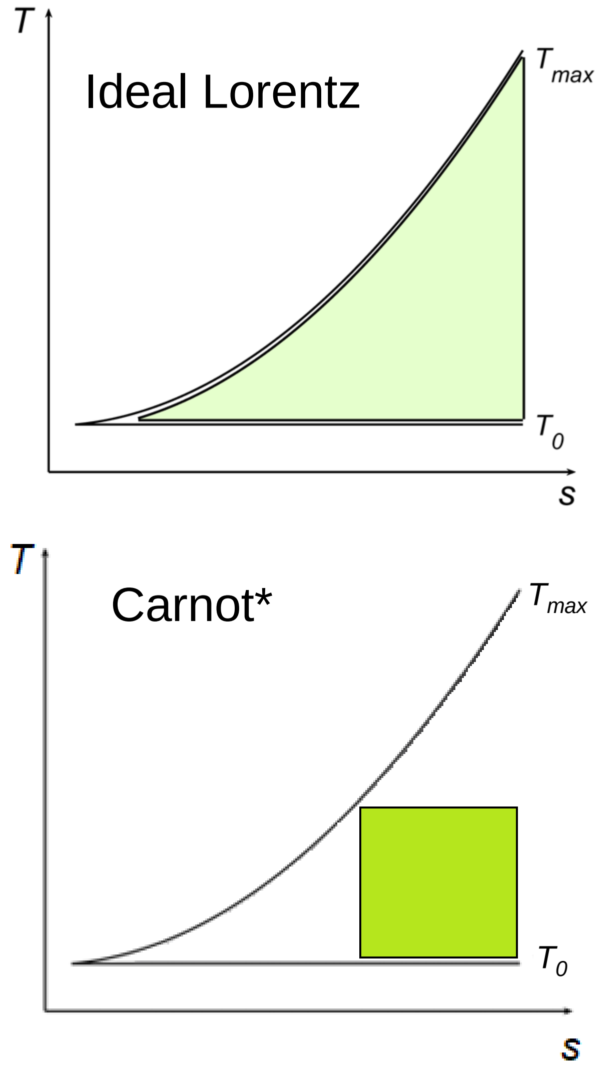
$$\eta_{\text{Lorentz}} = \frac{\dot{W}_{\text{rev}}}{\dot{Q}_{\text{avail.}}}$$

$$= 1 - \frac{T_0}{\Delta h/\Delta s} = 1 - \frac{T_0}{(T_{\text{max}} - T_0)/\ln(T_{\text{max}}/T_0)} < 1 - \frac{T_0}{T_{\text{max}}} = \eta_{\text{Carnot}}$$

but $> \eta_{\text{Carnot}^*}$

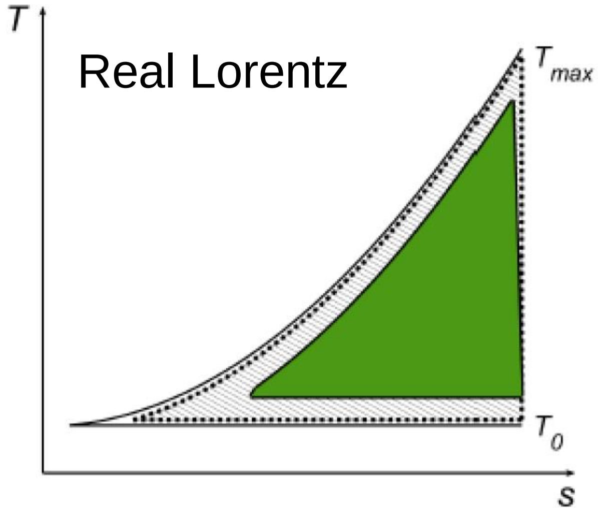
For $T_{\text{brine}} = 423\ \text{K}\ \&\ T_0 = 303\ \text{K}$

$$\boldsymbol{P_{\text{el}} = 80\ \text{kW/kg}_{\text{brine}}}$$
$$\boldsymbol{\eta_{\text{plant}} = 15.7\%}$$



Real Lorentz Cycle

Accounting for equipment performance



Heat Transfer

- $\Delta T_{pp,HEX} = 10K$
- $\Delta T_{pp,ACC} = 5K$
- $\eta_{fan} = 0.65$
- $\Delta P_{air,\ ACC} = 125\ Pa$

$$\boldsymbol{P_{el} = 45\ kW/kg_{brine}}$$
$$\boldsymbol{\eta_{plant} = 8.9\%}$$

Turbomachinery

- $\eta_{turbine} = 0.9$

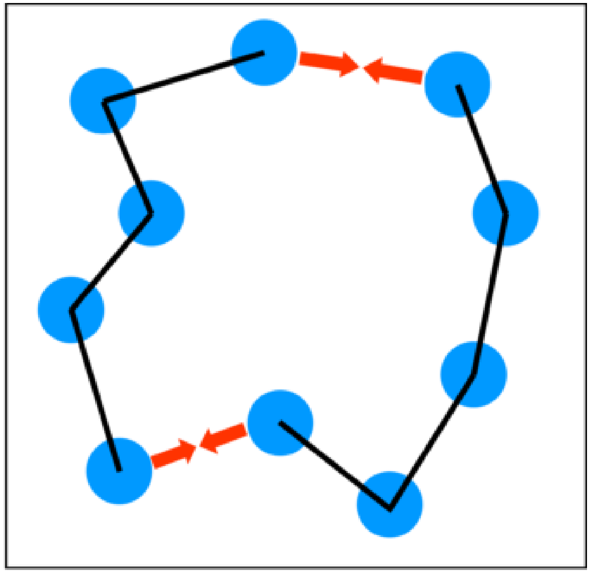
$$\boldsymbol{P_{el} = 39.5\ kW/kg_{brine}}$$
$$\boldsymbol{\eta_{plant} = 7.8\%}$$

~+ 60% wrt (butane) ORC plant!

How can we improve ORC performance?

Hypothesis #1: improve fluid selection

Approach:



- Physically-based equation of state: PC-SAFT

  Molecule: chains of spherical segments
- Idea: Optimize EoS parameters (*m*,σ,ε) + cycle parameters

  → Optimum Ideal Fluid & Cycle (Better Benchmark!)
- Look for fluids similar to ideal fluid

How can we improve ORC performance?

Hypothesis #1: improve fluid selection

- ➢ Optimal Pseudo-fluid simple cycle:

$$T_{\text{crit}} = 392\ K;\ \sigma = 3.9$$

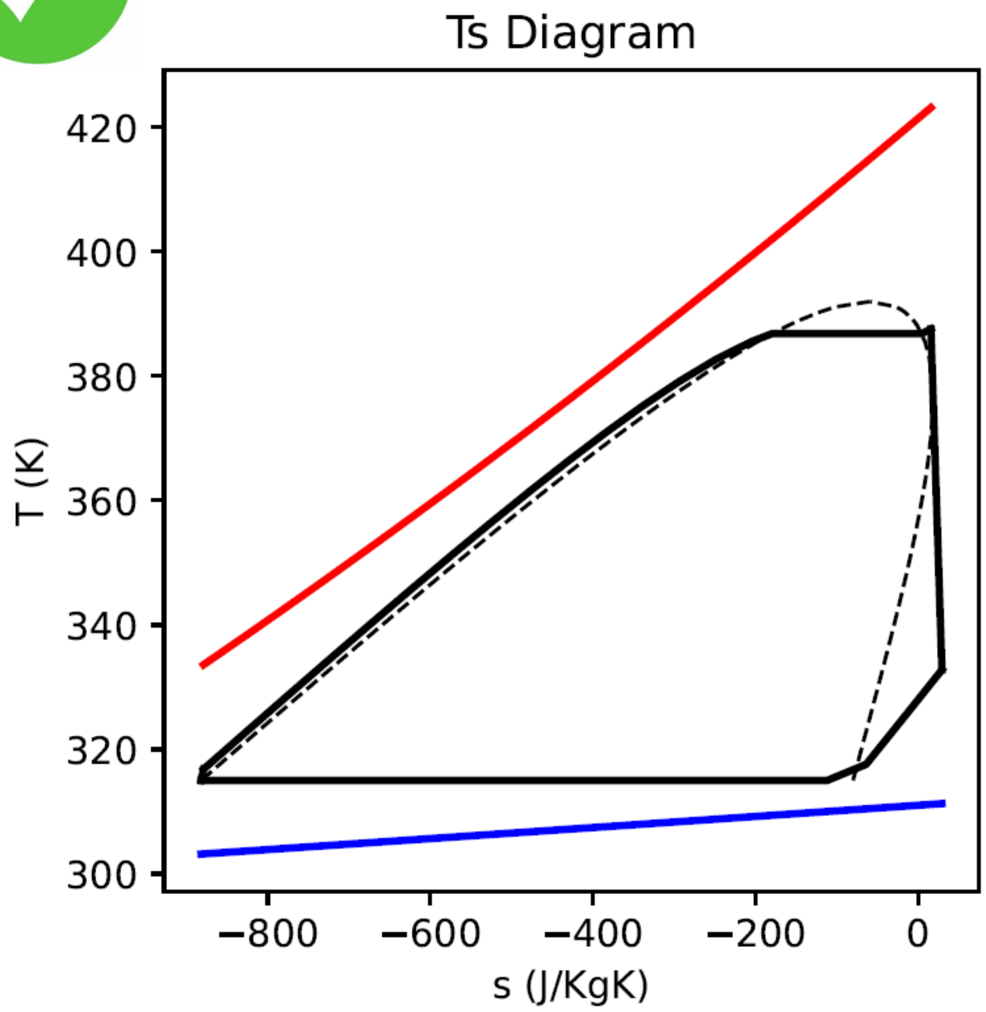
$$\boldsymbol{P_{\text{el}} = 35\ \text{kW/kg}_{\text{brine}}}$$

$$\boldsymbol{\eta_{\text{plant}} = 6.8\%}$$

< 15% gap with "real" Lorentz's cycle

- ➢ Best fluids: perfluorocarbons, CFC, HFO-1336mzz-E

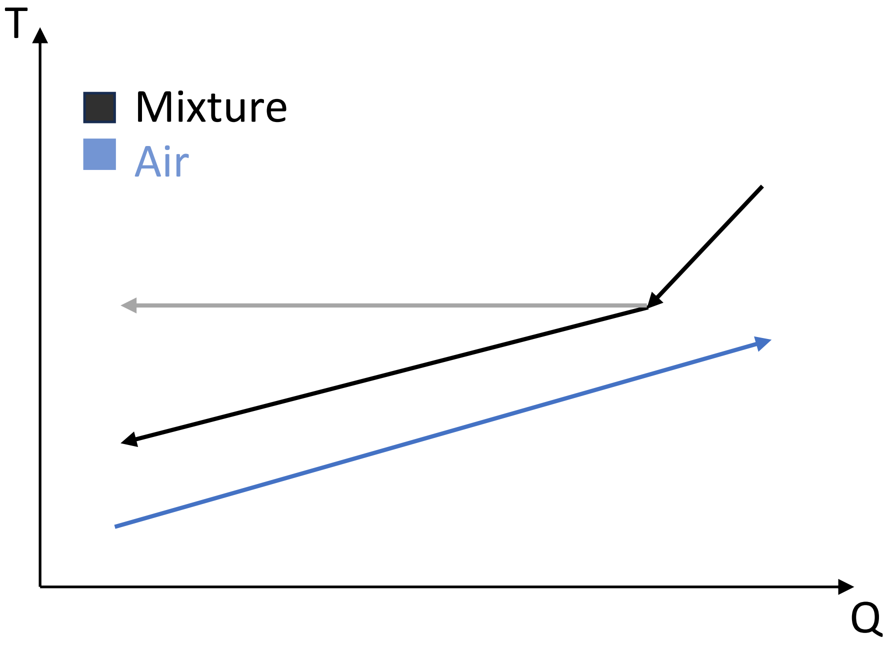
Expensive fluids and high GWP (except HFO)!

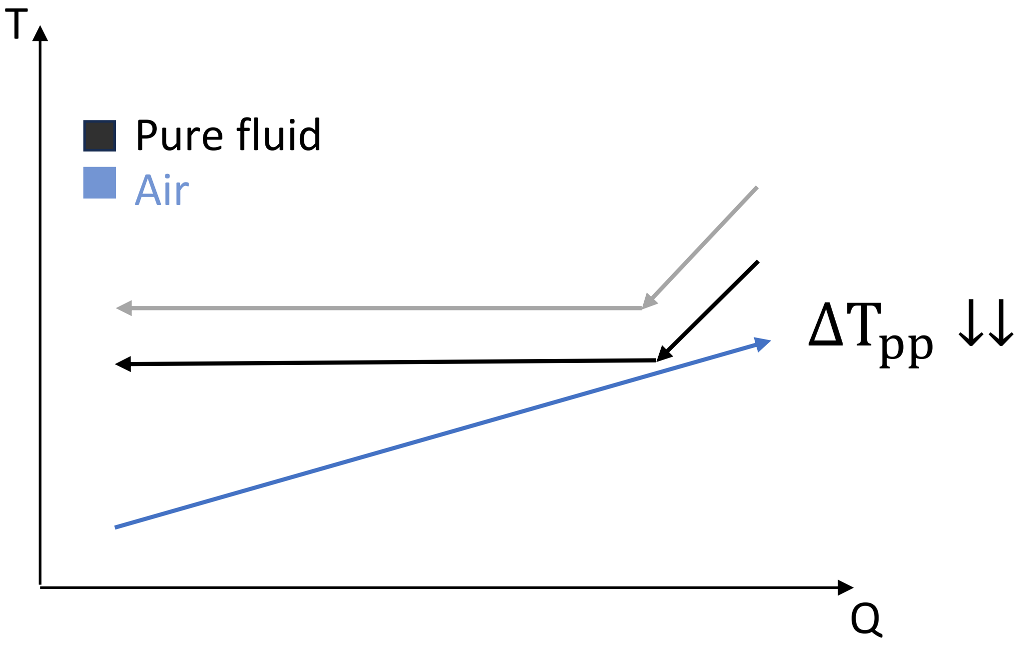


How can we improve ORC performance?

Hypothesis #2: use fluid mixtures

➢ Glide over condensation: lower T_{min} or ACC fan consumption





➢ Glide over evaporation: better “coupling” with thermal source

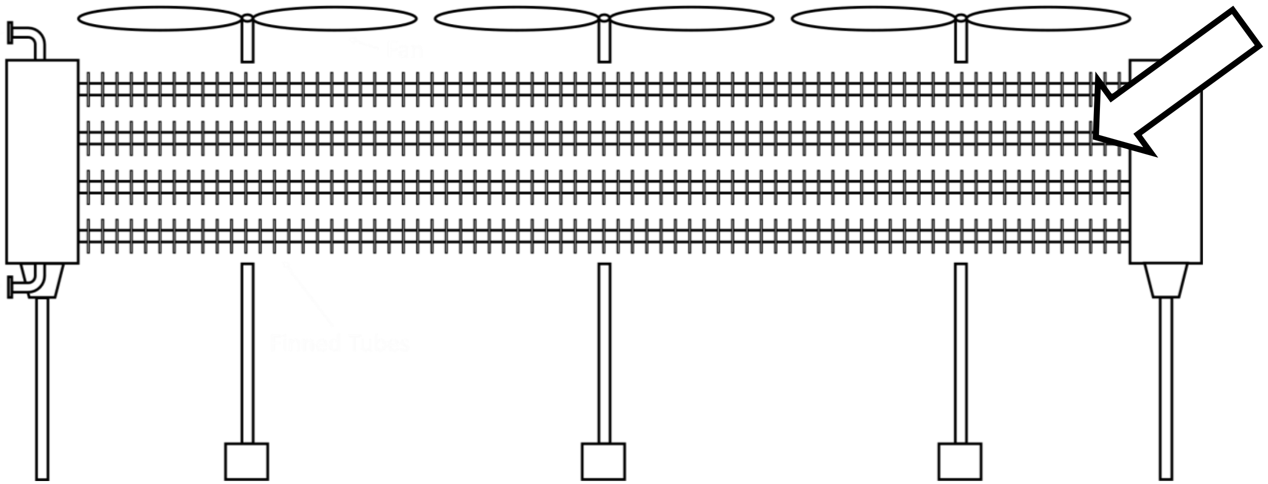
Ideal binary mixtures vs ideal pure fluids

Approach:

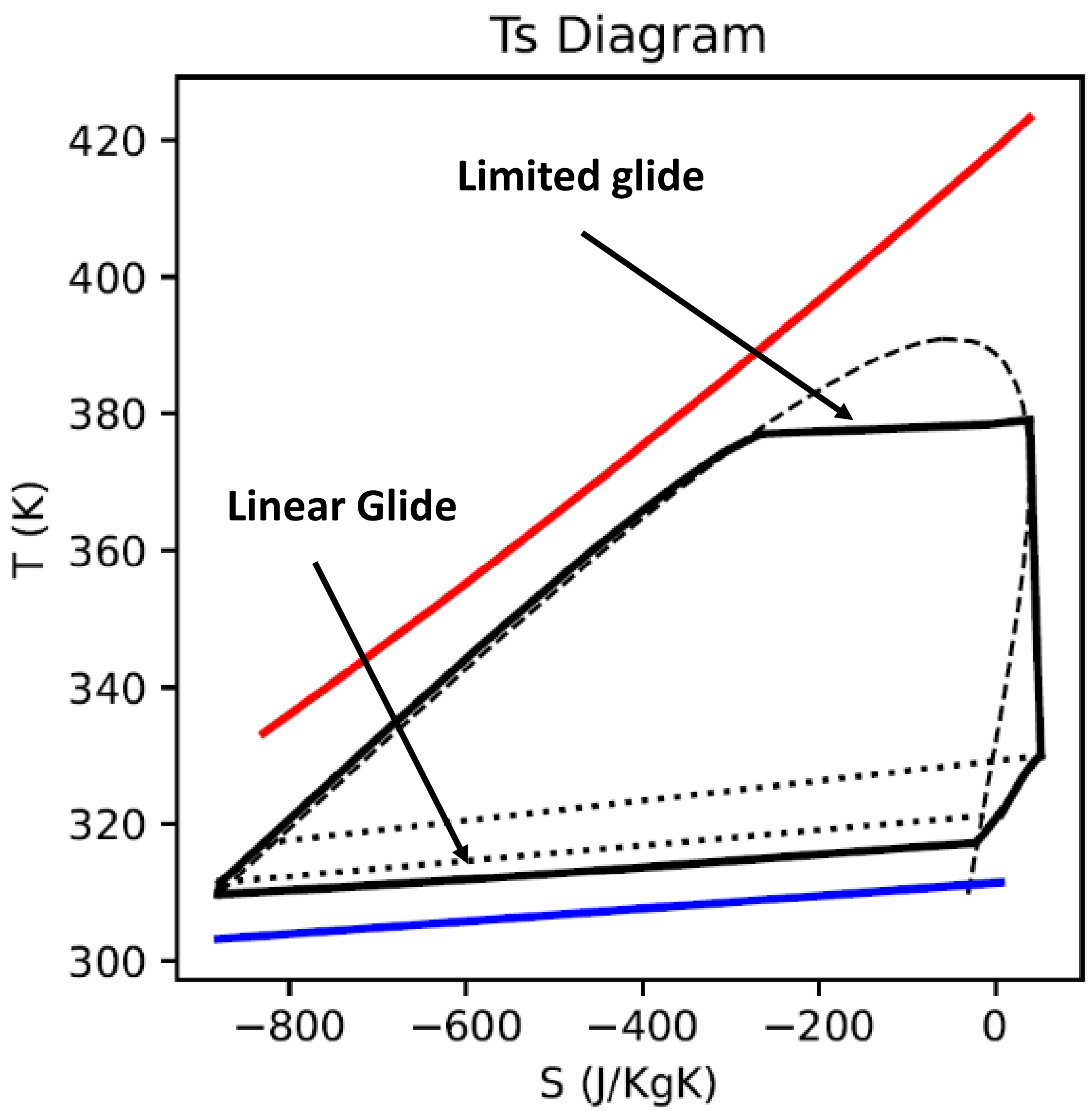
- Physically-based equation of state: PC-SAFT
- Optimize EoS parameters (*m*,σ,ε) of the two fluids & cycle parameters + aircooler preliminary design

→ Optimum pseudo-mixture & cycle

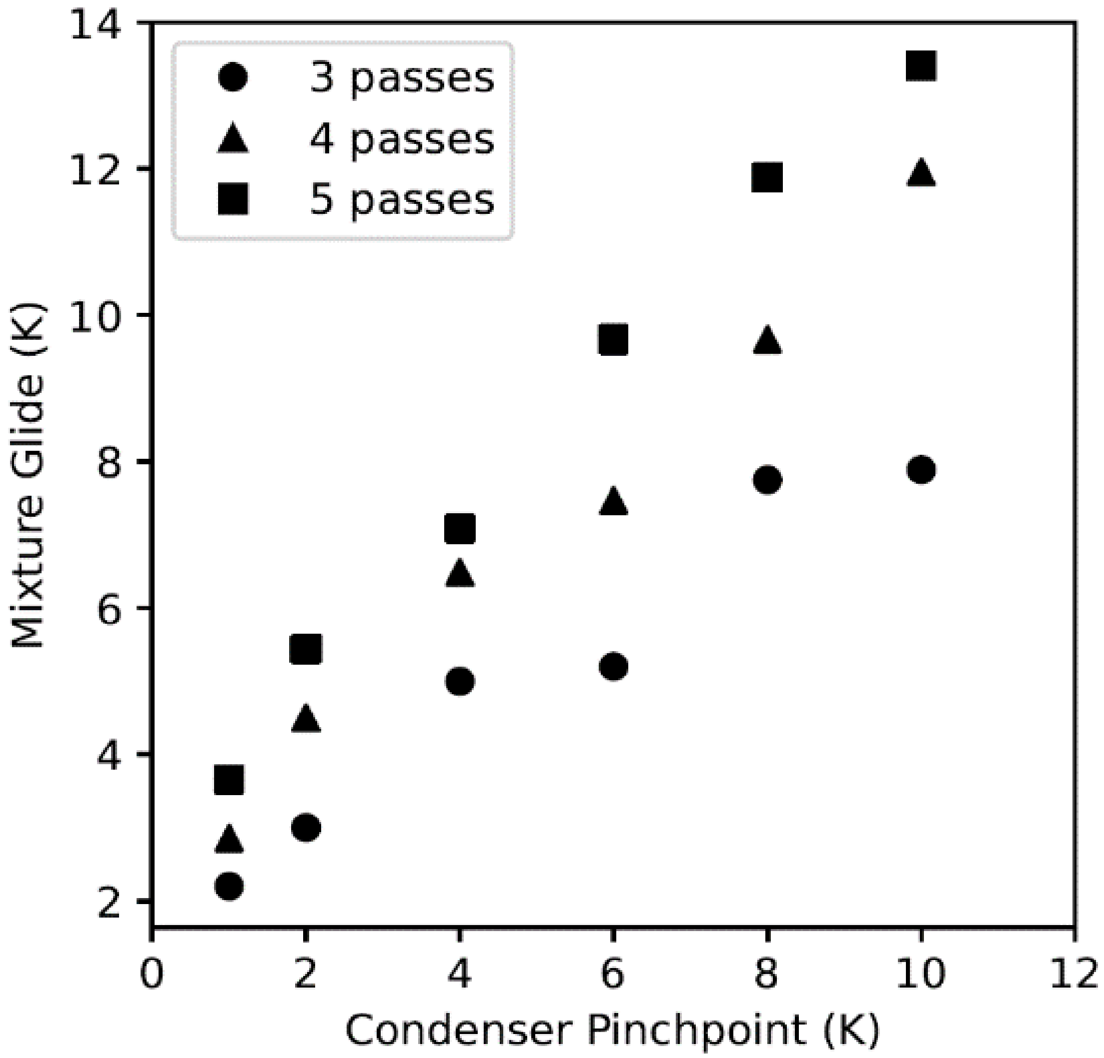
Degrees of freedom: ΔT_{pp} & # of rows/passes



Ideal binary mixtures

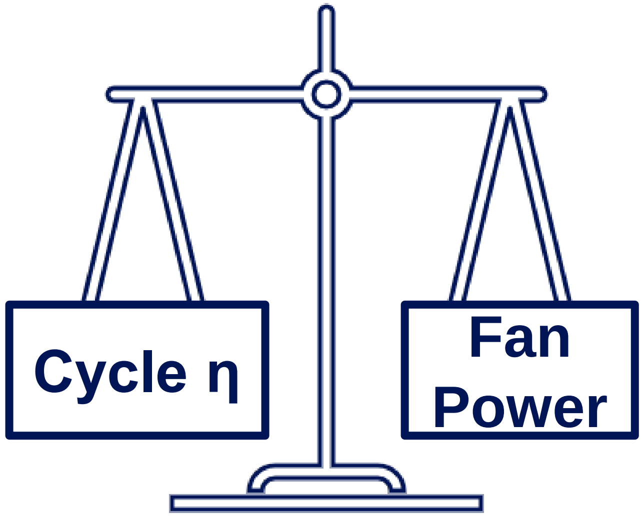


Optimal glide = f(Δ*T*pp; row #)



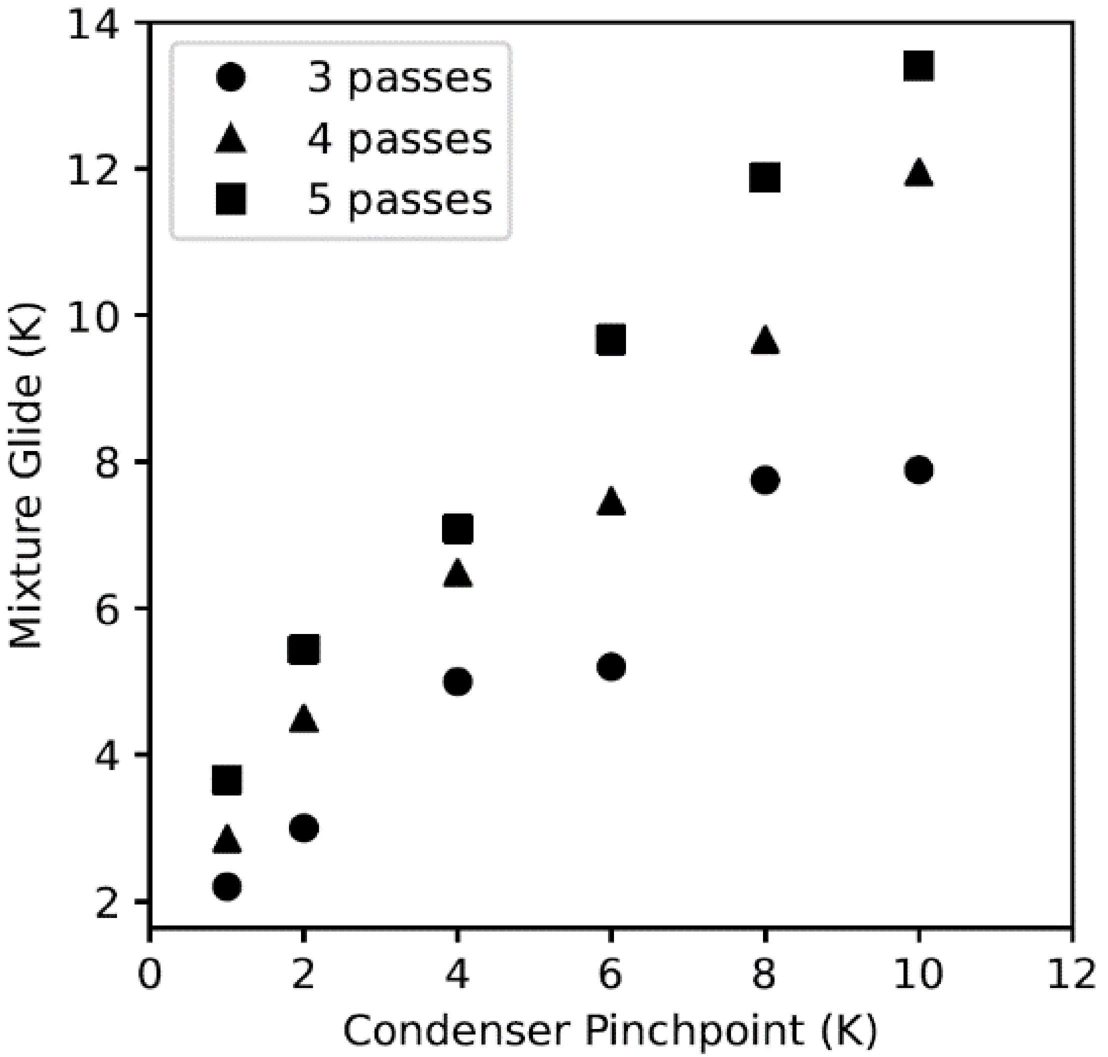
Ideal binary mixtures – optimal glide

Optimal glide results from

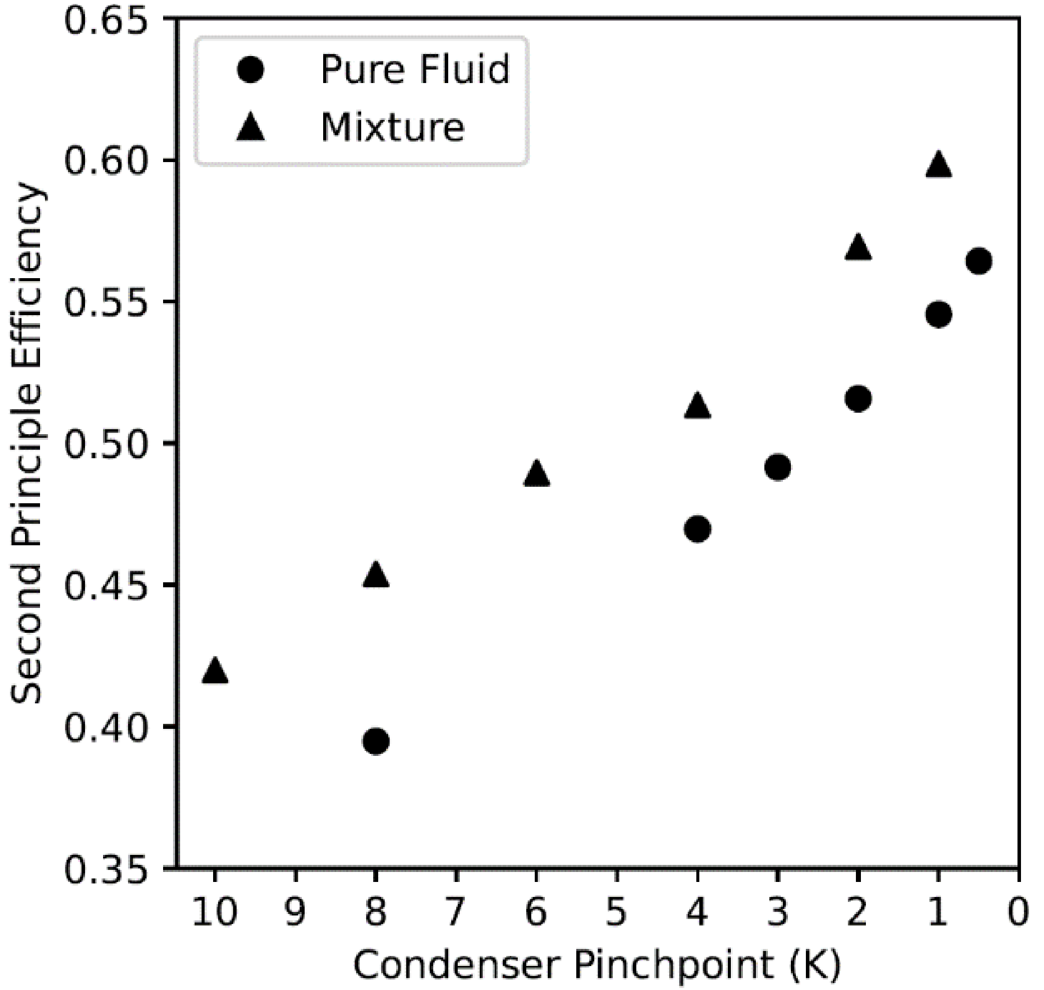


If $\Delta T_{\mathrm{PP}}\downarrow \rightarrow UA, A_{\mathrm{fr}} \uparrow\uparrow \rightarrow \Delta P_{\mathrm{air}}\downarrow\downarrow, P_{\mathrm{fan}} \downarrow$

$\rightarrow \Delta T_{\mathrm{air}}$ and $\Delta T_{\mathrm{glide}}$ reduced to increase η

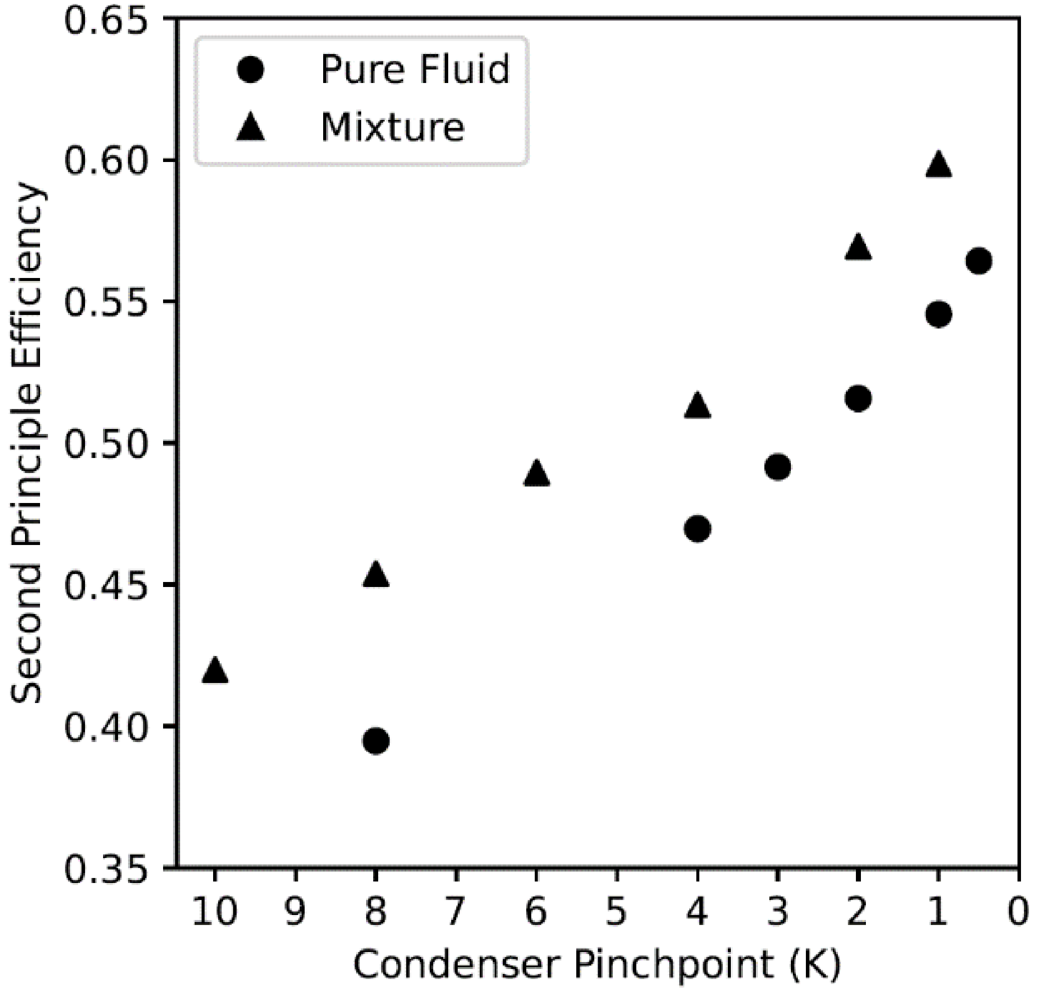


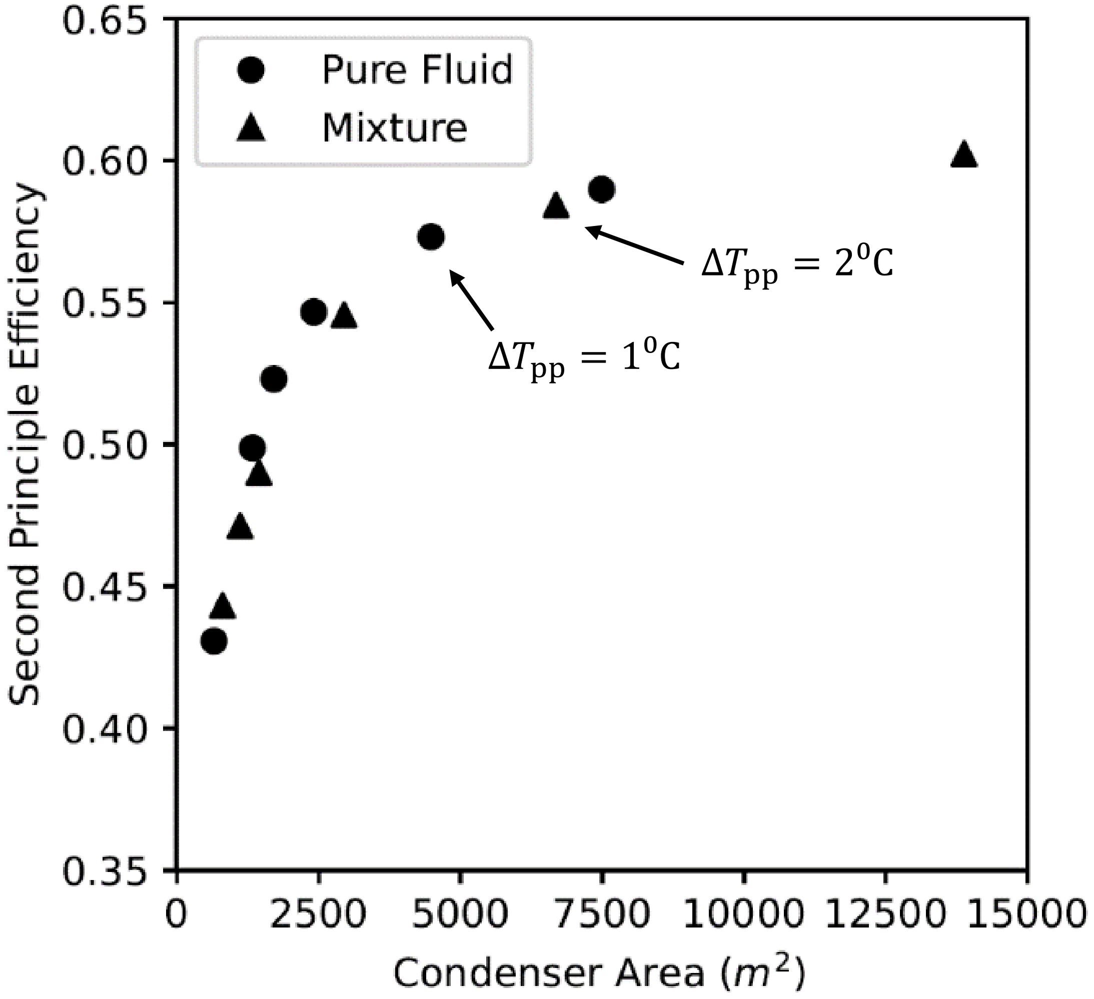
(Ideal) Mixtures vs pure fluids



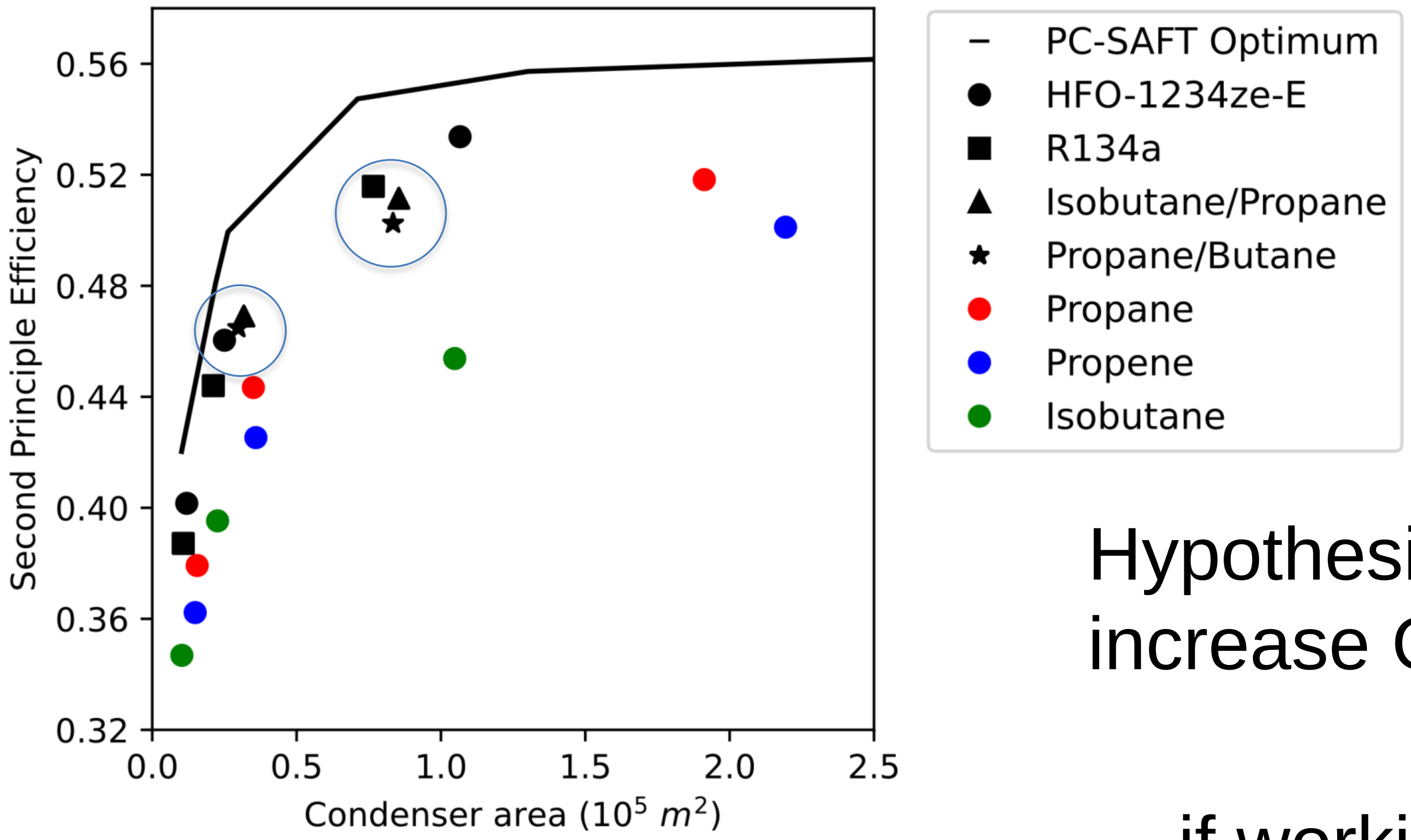
- $\eta_{II} = \frac{W_{net}}{W_{rev}}$
  $\rightarrow P_{el}\left[\frac{kW}{kg_{brine}}\right] = 80 \cdot \eta_{II}$
- Mixture allows for ~ +10% in plant power output
- Condenser A ↑↑ because both $\Delta T_{ml}, h_{mixt}$ ↓
- Once-through boiler in place of kettle boiler

(Ideal) Mixtures vs pure fluids





Real mixtures vs pure fluids

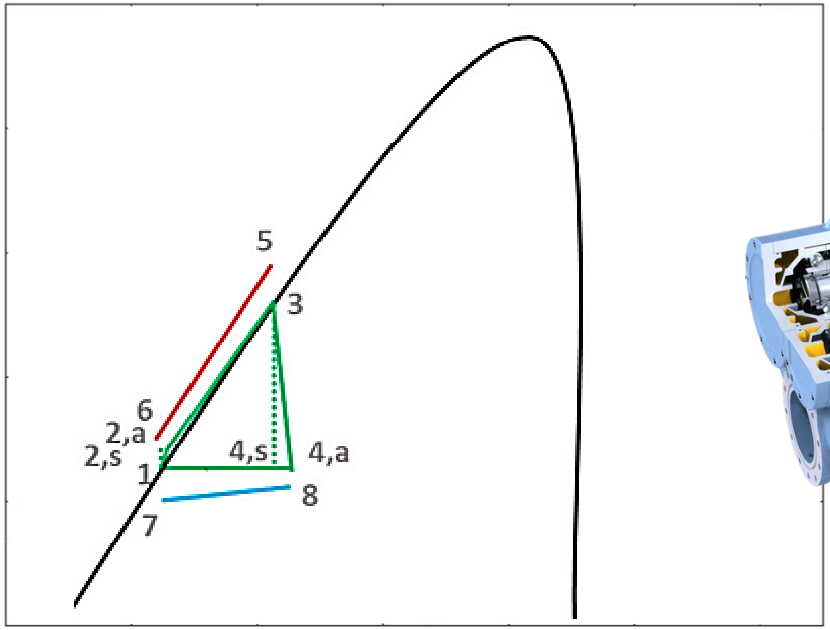


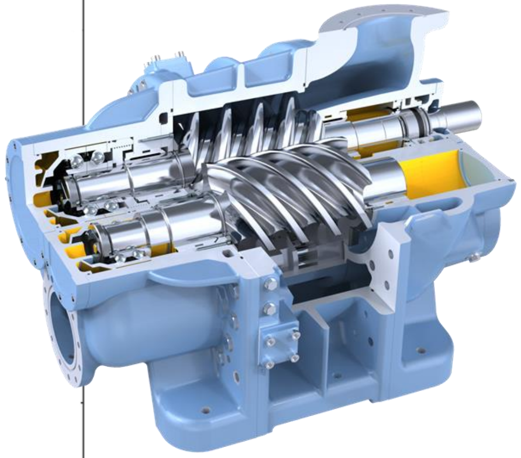
Hypothesis #2: use of mixtures to increase ORC plant η ✓

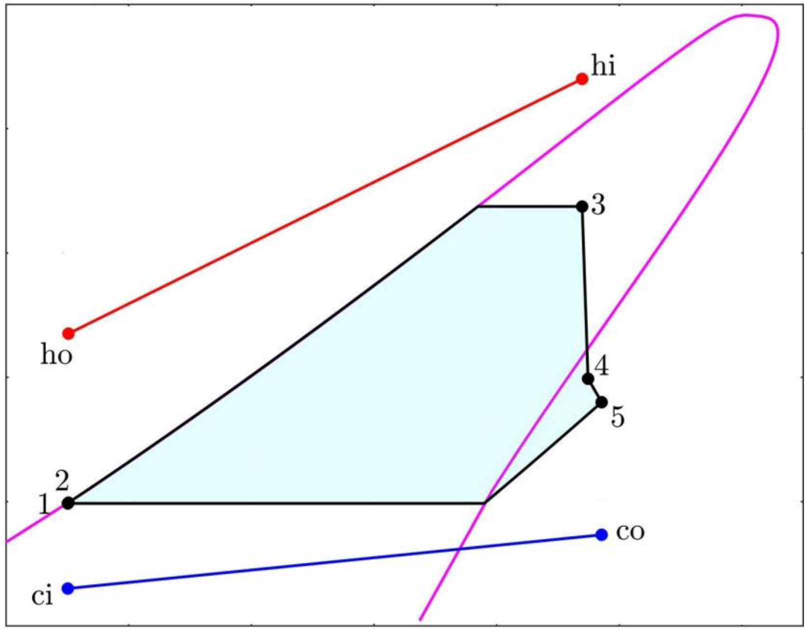
if working fluids = hydrocarbons

How can we improve ORC performance?

Hypothesis #3: two-phase expansion (TBA). η_{expander} is key!







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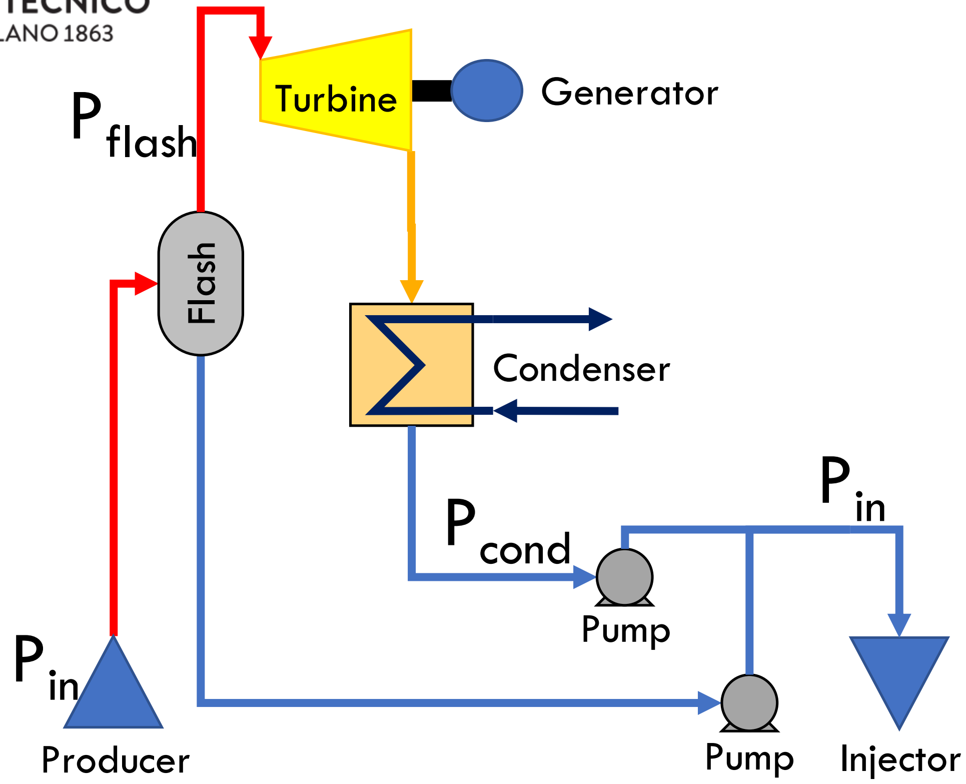
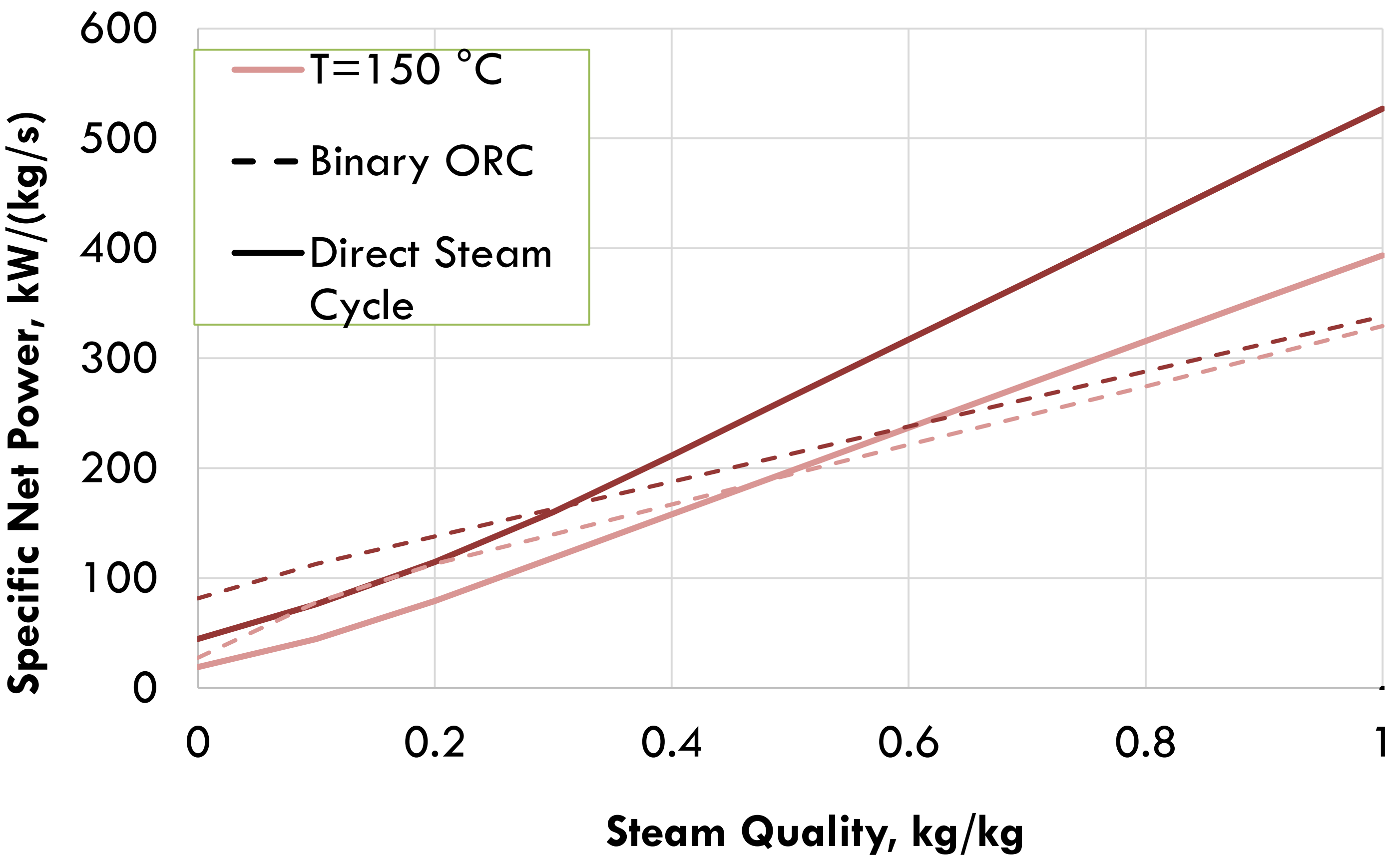
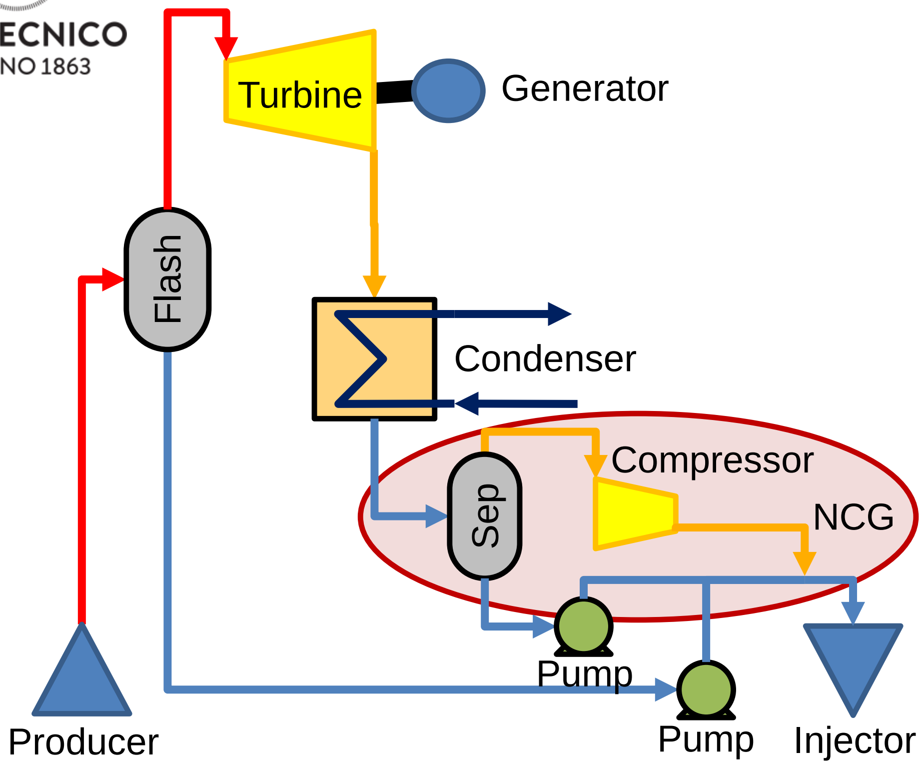
- ➢ NASA Report 32-987: Acceleration of Liquids in 2-Phase Nozzles

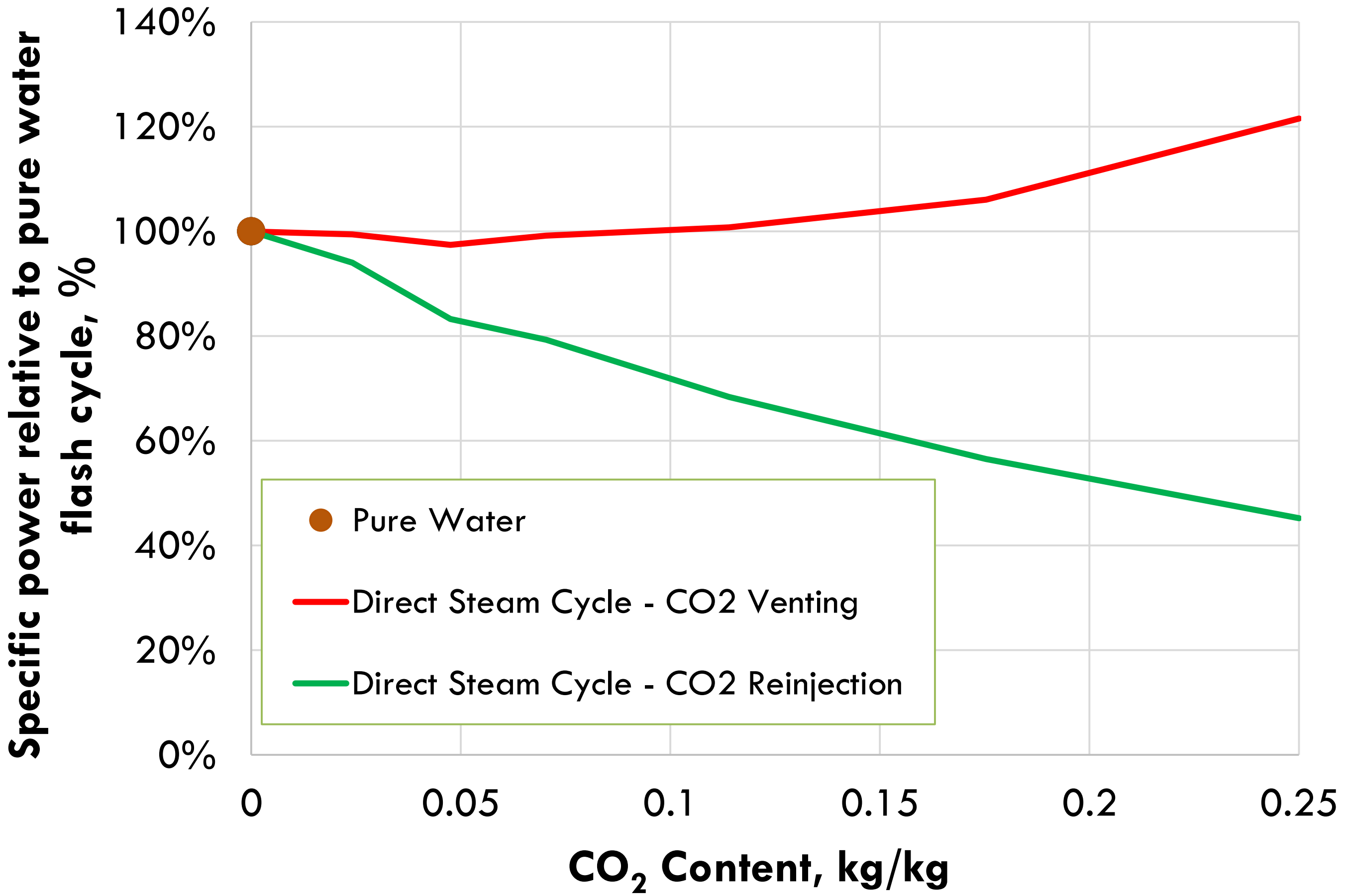
Flash Cycle vs. ORC





Flash Cycle vs. ORC – Effect of CO_2





ORC best solution also for higher *T* & vapor quality of the brine?

Conclusions

- ORC technology is efficient! Economic & environmental reasons drive working fluid choice, thus impacting plant efficiency
- Glide over condensation offers limited thermodynamic benefit
- Hydrocarbon mixtures enable cycle efficiencies similar to those of the best (pure) refrigerants, but system complexity increases
- ORC with 2-phase expansion can be an attractive solution if efficient expanders are available
- If CO_2 fraction in the brine is high, minimize brine flashing and consider cooling it down in an ORC system

THANK YOU