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Impact of selective admixture of additives to carbon dioxide on the size of sCO_2 power cycle key components

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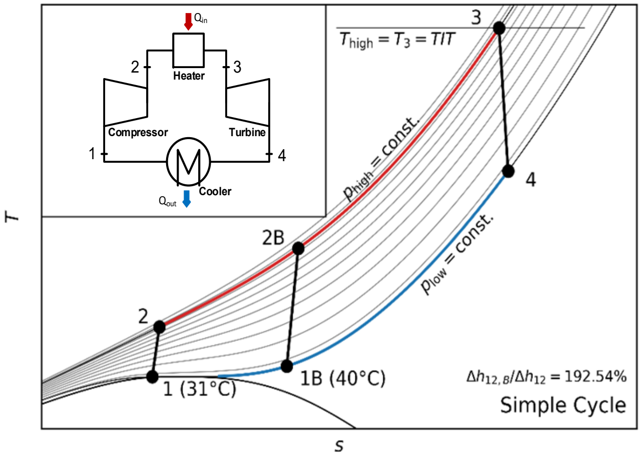
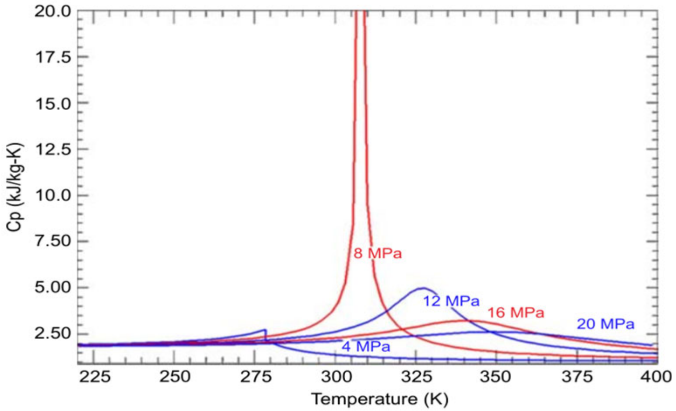
Motivation

- The efficiency of sCO_2-cycles is essentially connected to a state point at the compressor being close to the critical point (30.98 °C, 7.377 MPa)
- Stable operation requires sufficient recooling → tradeoff between component sizes and process conditions → e.g. arid regions / air cooling



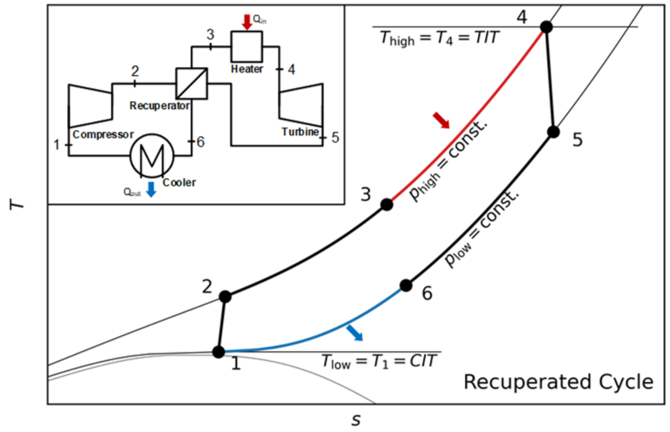


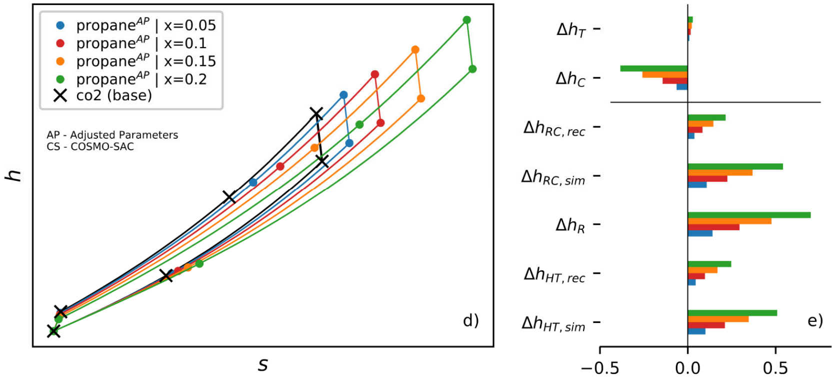
Source: Brun et. al.; Fundamentals and Applications of Supercritical Carbon Dioxide (sCO2) Based Power Cycles

Motivation

- The efficiency of sCO_2-cycles is essentially connected to a state point at the compressor being close to the critical point (30.98 °C, 7.377 MPa)
- Stable operation requires sufficient recooling → tradeoff between component sizes and process conditions → e.g. arid regions / air cooling
- Mixtures allow to adapt the process to better fit individual conditions
- Additives can bring significant shifts in the enthalpy differences which may affect the size of components

→ A precise evaluation of mixture potentials requires to include component sizes





Size correlations – Requirements and boundary conditions

- Relative comparison of the geometric change of the main components → heat exchanger & turbomachinery
- Only based on properties typically available in cycle analysis / optimization

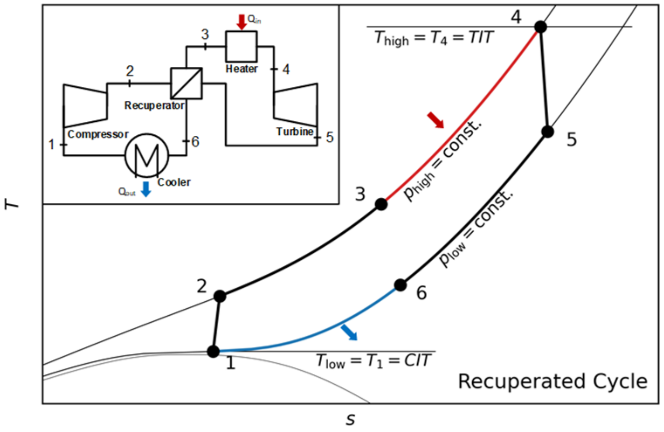


Fig. a): Block diagram and *T-s* diagram representation of the Recuperated Cycle

Boundary conditions and assumptions

- Regardless of the mixture, each component is always related to the same design (heat exchangers)
- Key design variables (e.g. channel diameters, rotating speeds) are kept constant
- Constant mass flow (no taps, flow splits)
- Constant ΔT in the cooler and the heater

Size correlations – Heat exchangers

- HEX volume may be oriented on the core volume:

$$V_{HX} \approx A_{\mathrm{cs}} \cdot L_{\mathrm{c}}$$

- The cross section can be referred directly to the mass flow, the mean density, and the mean velocity

$$A_{cs} = \frac{\dot{m}}{\bar{c} \cdot \bar{\rho}}$$

- Assumption of constant $\bar{c}$ allows to write:

$$f_{A,HX} = \dot{m} \cdot (\bar{\rho})^{-1}$$

- $\dot{m}$ (relative factor) is derived from the assumption of a constant heat flux in the heater for all fluids:

$$\dot{m} = \frac{\dot{Q}_{\mathrm{H}}}{\Delta h_{\mathrm{H}}} \overset{\mathrm{def}}{=} \frac{\mathrm{const.}}{\Delta h_{\mathrm{H}}} \mid \dot{Q}_{\mathrm{H}} \overset{\mathrm{def}}{=} \dot{Q}_{\mathrm{H,CO2}} \overset{\mathrm{def}}{=} \dot{Q}_{\mathrm{H,Mix}} \overset{\mathrm{def}}{=} \dot{Q} \overset{\mathrm{def}}{=} \mathrm{const.}$$

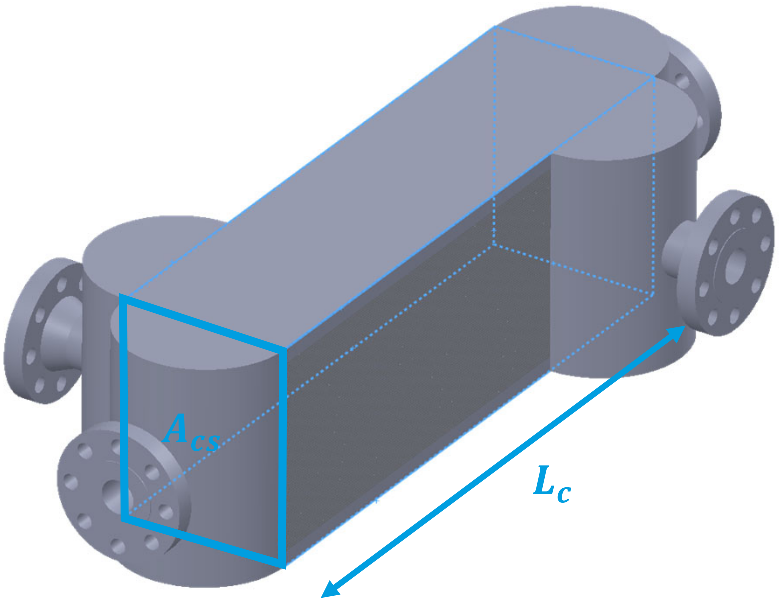


Fig. a): CAD-example of a printed circuit heat exchanger (PCHE)

Size correlations – Heat exchangers

- Starting point for a length factor is the general heat transfer equation for pipe flow:

$$\dot{Q} = \Delta h \cdot \dot{m} = \bar{\alpha} \cdot A_{\mathrm{surf}} \cdot \Delta T = \bar{\alpha} \cdot \pi \cdot d \cdot L \cdot \Delta T$$

- Conversion to L and expansion with Nu yields:

$$L = \frac{\Delta h \cdot \dot{m}}{\bar{\lambda} \cdot \mathrm{Nu} \cdot \pi \cdot \Delta T}$$

- Further expansions and cutting the constants allows the following expression:

$$f_{L,\mathrm{HX}} = \frac{\Delta h \cdot \dot{m} \cdot \left(\frac{\bar{c_p} \cdot \bar{\eta}}{\bar{\lambda}}\right)^{-n}}{\Delta T \cdot \bar{\lambda} \cdot \left(\frac{\bar{\rho}}{\bar{\eta}}\right)^{0.8}}$$

- Finally, a relational value for the HEX-volume is given by:

$$f_{V,HX} = f_{A,HX} \cdot f_{L,HX}$$

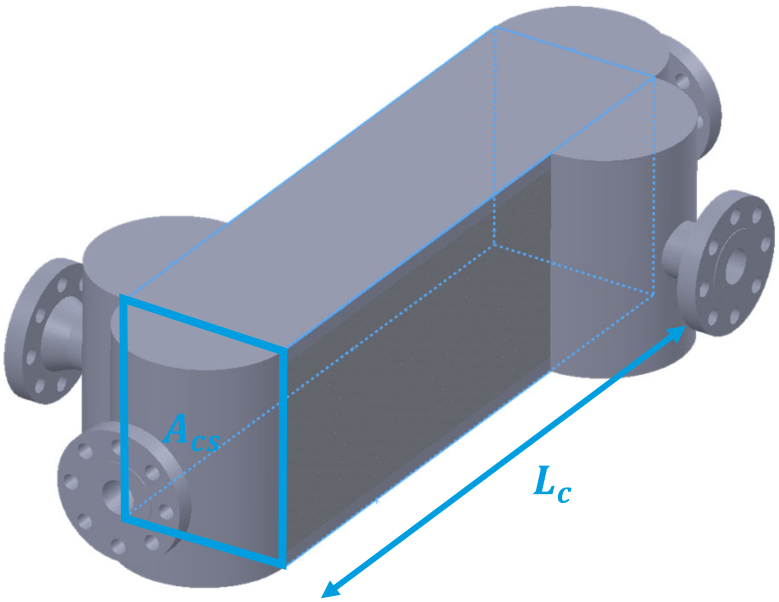


Fig. a): CAD-example of a printed circuit heat exchanger (PCHE)

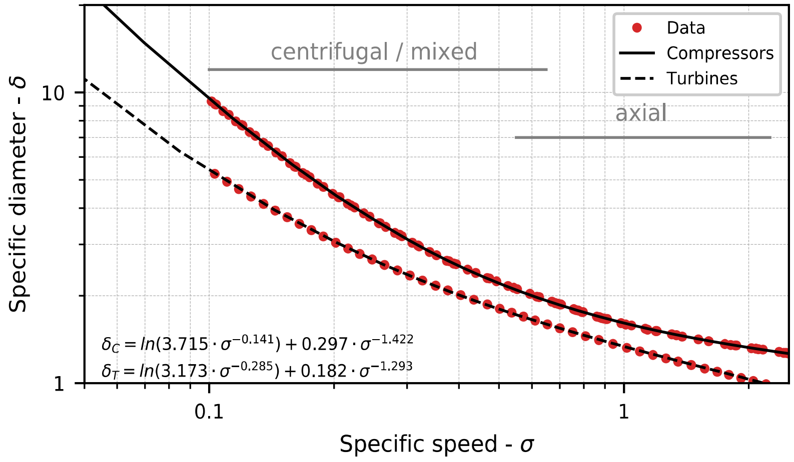
Size correlations – Turbomachinery

- The size of the turbomachinery requires a consideration of its construction type
- Oriented on dimensionless parameters for a single stage machine
- A formulation of the specific speed depending only on process and fluid parameters is given by:

$$\sigma = n \cdot \frac{2 \cdot \sqrt{\pi \cdot \dot{V}}}{(2 \cdot \Delta h)^{3/4}} \rightarrow \sigma^* = \frac{\sqrt{\dot{m}/\rho}}{\Delta h^{3/4}}$$

- The specific diameter δ can now be obtained by the lines of the highest efficiency in the Cordier diagram
- Reasonable results (in the scope of the diagram) require reference to an arbitrary baseline value $\sigma_{\mathrm{CO2,Ref},i}$:

$$\sigma_{\mathrm{MIX},i} = \sigma_{\mathrm{CO2,Ref},i} \cdot \frac{{\sigma^*}_{\mathrm{MIX},i}}{{\sigma^*}_{\mathrm{CO2},i}}$$



Application to selected mixtures

- Consideration of two rather simple cycles previously used in a screening
- Parameters oriented at an exemplary WHR application with potential air recooling to elevated ambient conditions
- Selection of 4 admixtures (H_2S, $\mathbf{C_3H_8}$, Kr, **Xe**), which had shown a significant increase in efficiency at least in one of the two process architectures and are also considered in recent literature

Boundary condition	Symbol	Value
Min. temperature	$\vartheta_{\mathrm{low}} \equiv \mathrm{CIT}$	40 °C
Max. temperature	$\vartheta_{\mathrm{high}} \equiv \mathrm{TIT}$	500 °C
Lower pressure level	p_{low}	7.4 MPa
Upper pressure level	p_{high}	20 MPa
Compressor efficiency	η_{C}	0.8
Turbine efficiency	η_{T}	0.9
Min. pinch point difference recuperator	ΔT_{R}	10 K

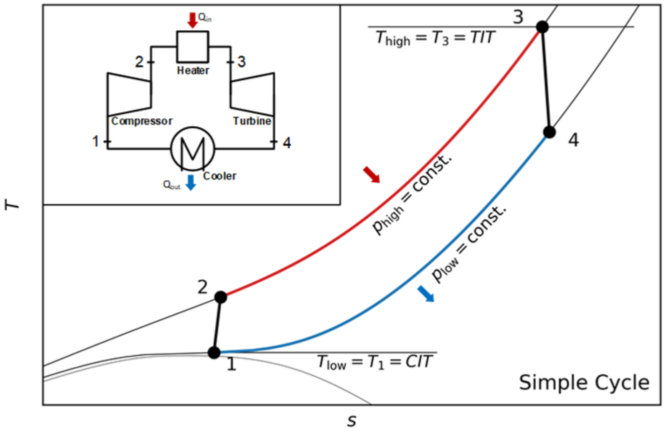


Fig. a): Block diagram and *T-s* diagram representation of the Simple Cycle

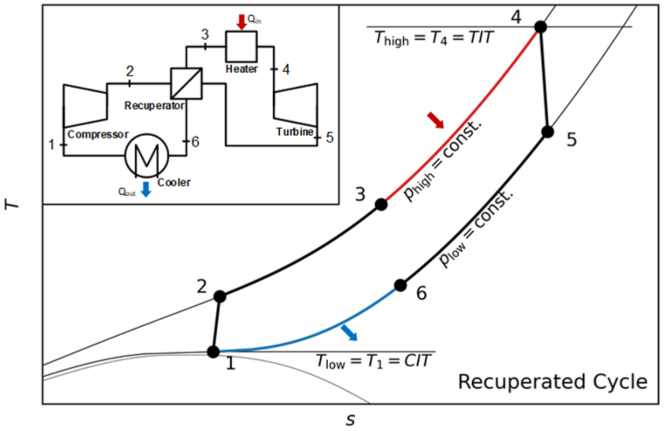
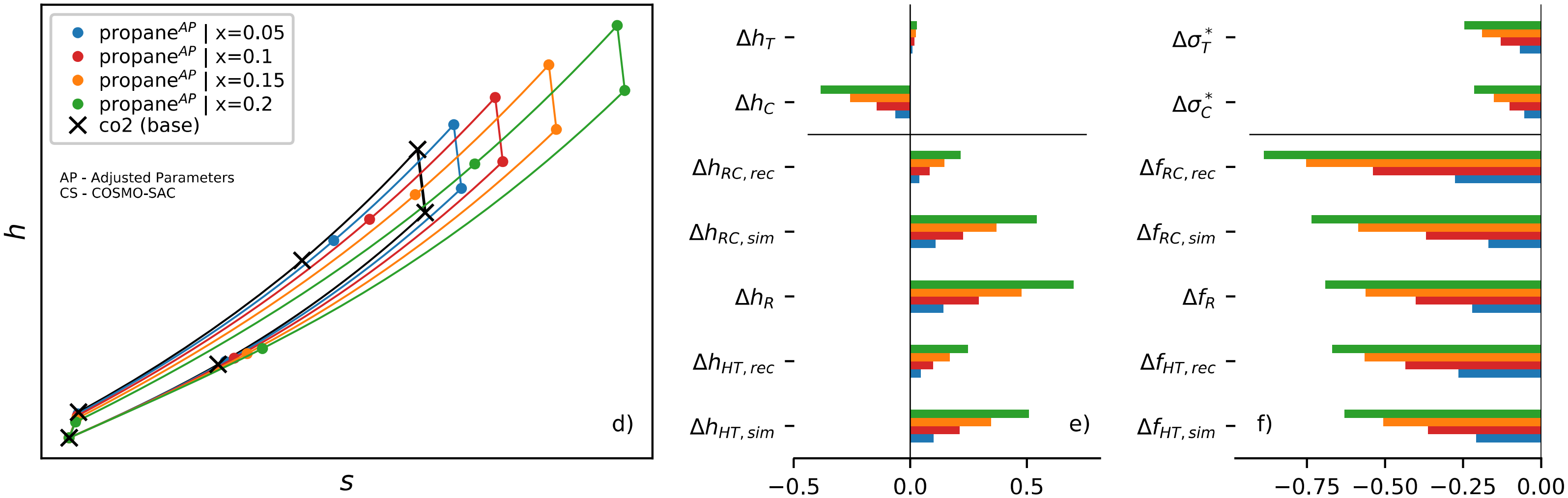


Fig. b): Block diagram and *T-s* diagram representation of the Recuperated Cycle

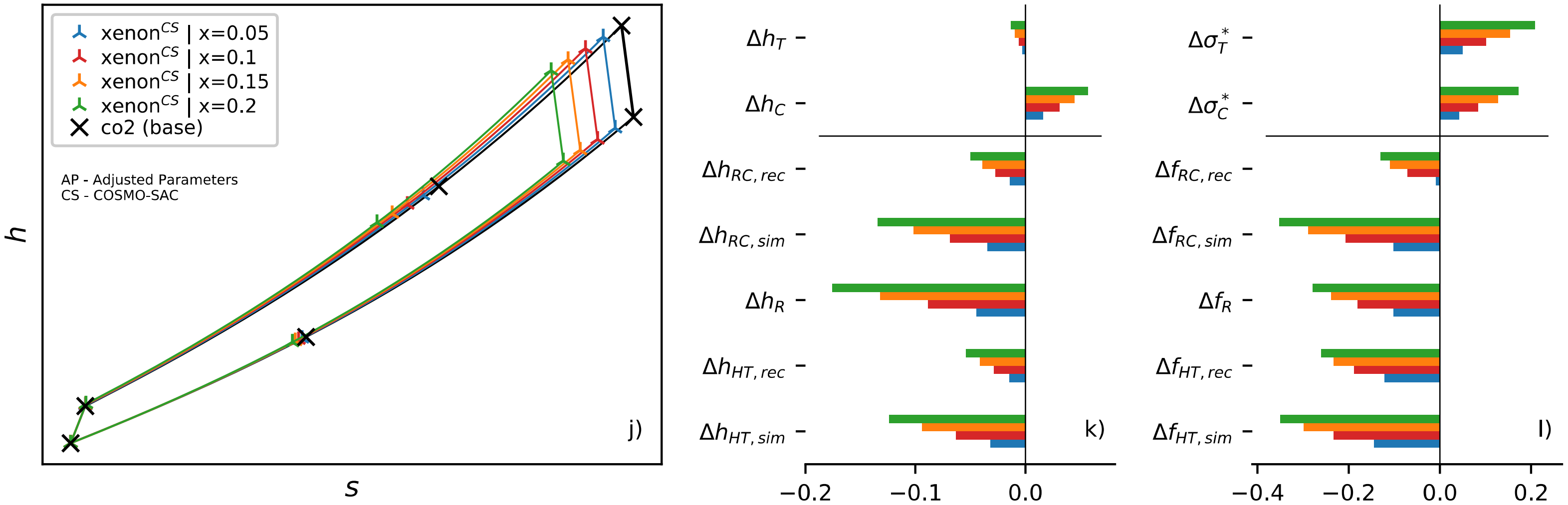
Application to selected mixtures – $CO_2 + C_3H_8$

- Increasing changes to higher values for *h* and *s* with increasing admixture of propane
- Reduction of Δh in the compressor, only slight changes for the turbine
- Increases in Δh for all HEX
- Nearly equivalent reduction in $\Delta\sigma^*$ for both turbomachines
- Distinct reduction of size up to approx. 80% for all HEX (despite increases in Δh)
- Both effects may result from higher ρ and higher c_p at higher admixtures



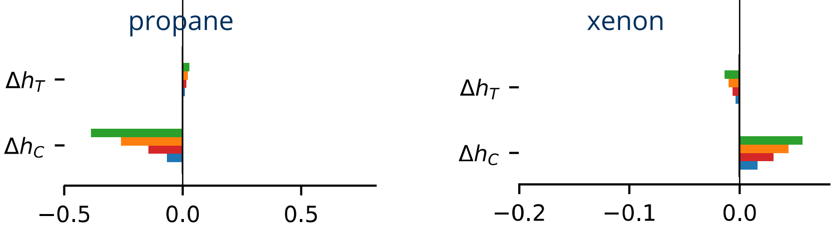
Application to selected mixtures – CO_2 + Xe

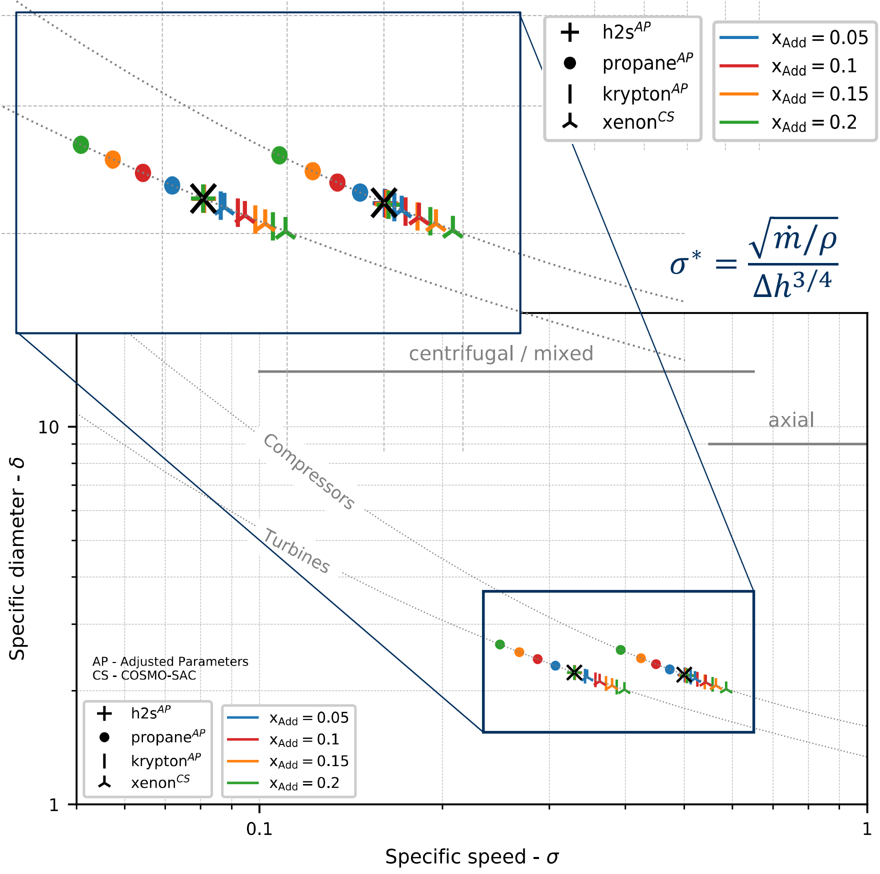
- Decreasing values for *h* and *s* with increasing admixture of xenon
- Shapes of the isobars remain nearly unaffected
- Decreasing values for Δh and Δf with increasing admixture
- Reduction of size up to approx. 38% for all HEX (despite increases in Δh)



Application to selected mixtures – Cordier diagram

- Variations are also visible in the Cordier diagram
- Changes mainly driven by density / heat capacity rather than enthalpy differences
- Addition of propane tends to higher diameters / lower speeds
- Addition of xenon tends to lower diameters / higher speeds
- Even small admixtures lead to visible changes, but may be tolerated





$$\sigma^* = \frac{\sqrt{\dot{m}/\rho}}{\Delta h^{3/4}}$$

Conclusion & Next steps

- Component sizes may vary significantly even at small amounts of additive
- Variations are not necessarily bound only to the enthalpy differences in the devices and may not follow uniform trends regarding the concentration
- Provides challenges but also potentials for the use of mixtures e.g. reduction in component sizes
- We have shown a simple approach to consider sizes in early evaluation stages of mixtures

Next steps:

- Expansion to more complicated cycles
- Verification by exemplary comparison with more complex design approaches
- Comparison with experimental data from our sCO_2 test facilities
    - suCOO-Lab test facility, TU Dresden
    - CARBOSOLA test facility, HZDR

»Wissen schafft Brücken.«

Thank you for listening.