Mixing it up: the effect of dopants on the design of CO_2 cycle and turbine

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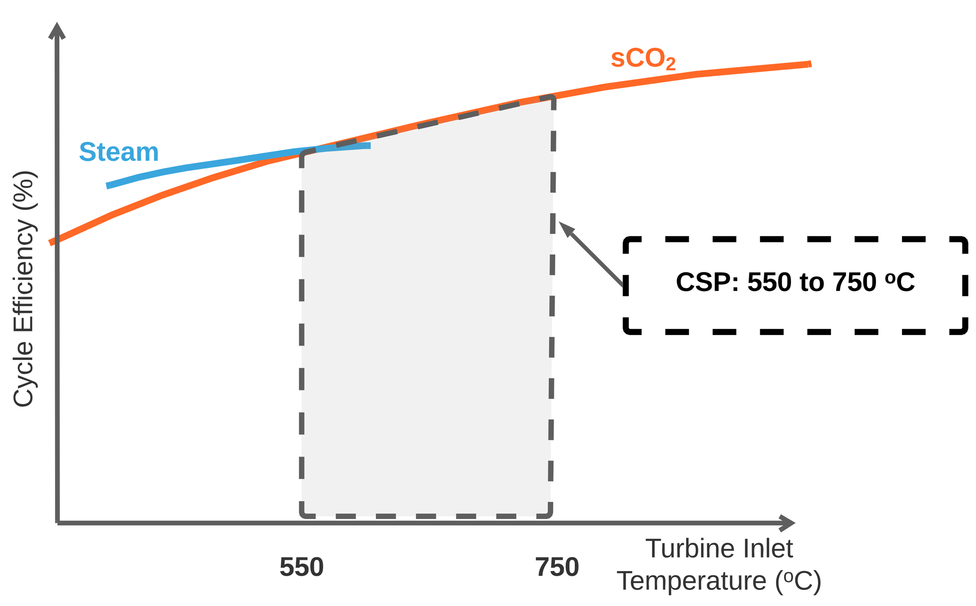
Technological context

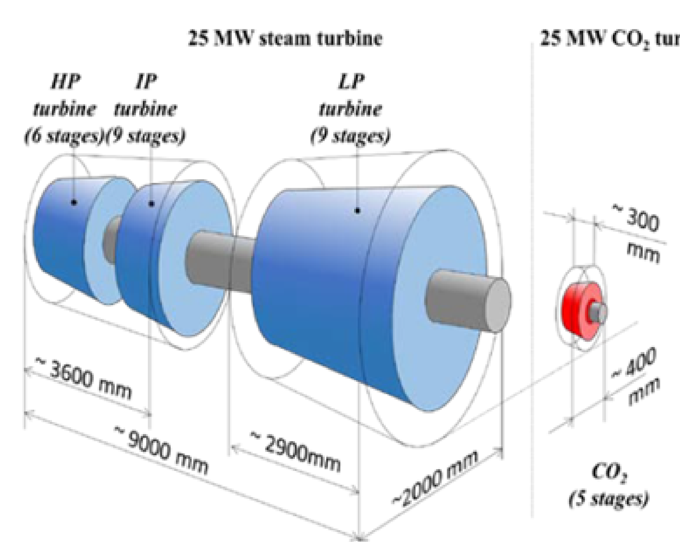
Supercritical CO_2 cycles

Supercritical carbon dioxide (sCO_2) was identified as a viable working fluid for power plants as early as the 1960's. Research has shown that it may outperform state-of-the-art steam cycle for turbine inlet temperatures >550 ºC, which makes it a valuable asset for advanced concentrated solar power (CSP)



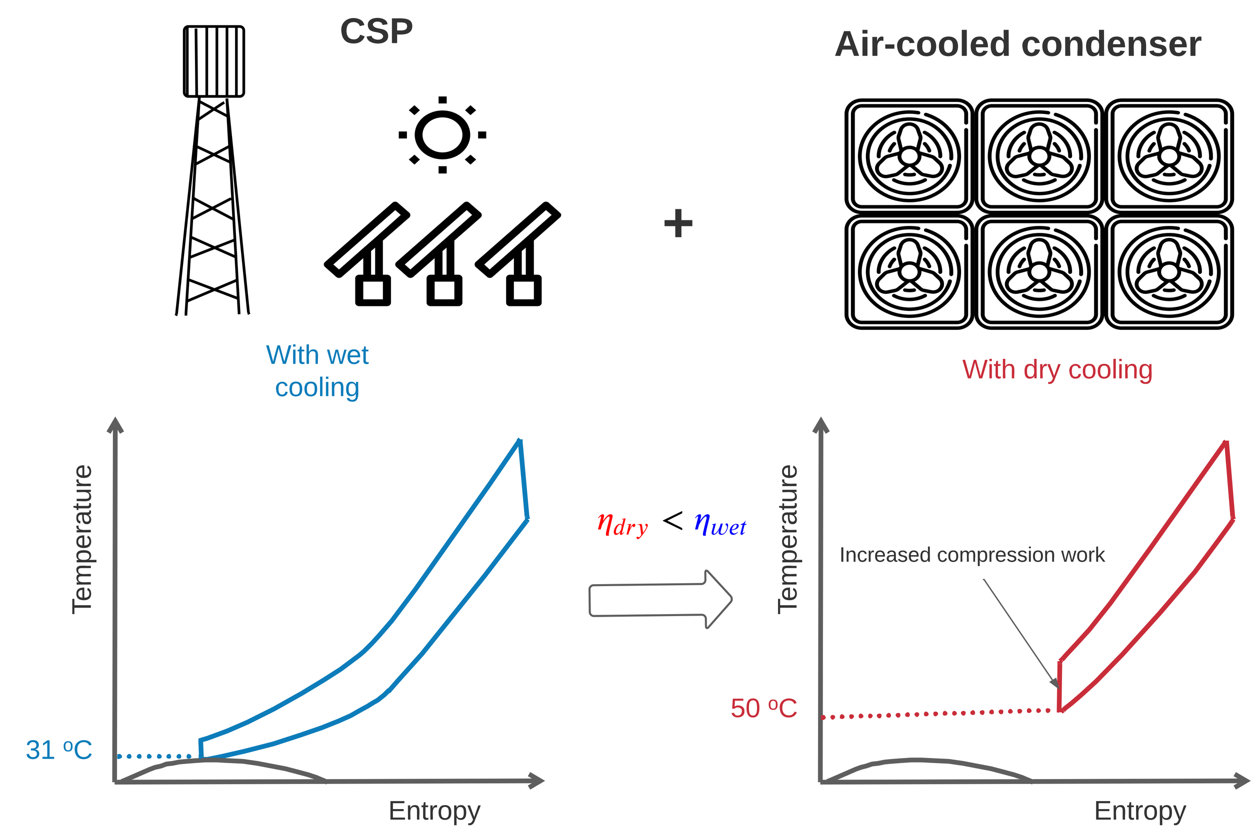
Why CO_2?

- Abundant
- Cheap
- Non-toxic
- Non-flammable
- Thermally stable at high temperatures
- Good cycle efficiency
- Compact turbomachinery



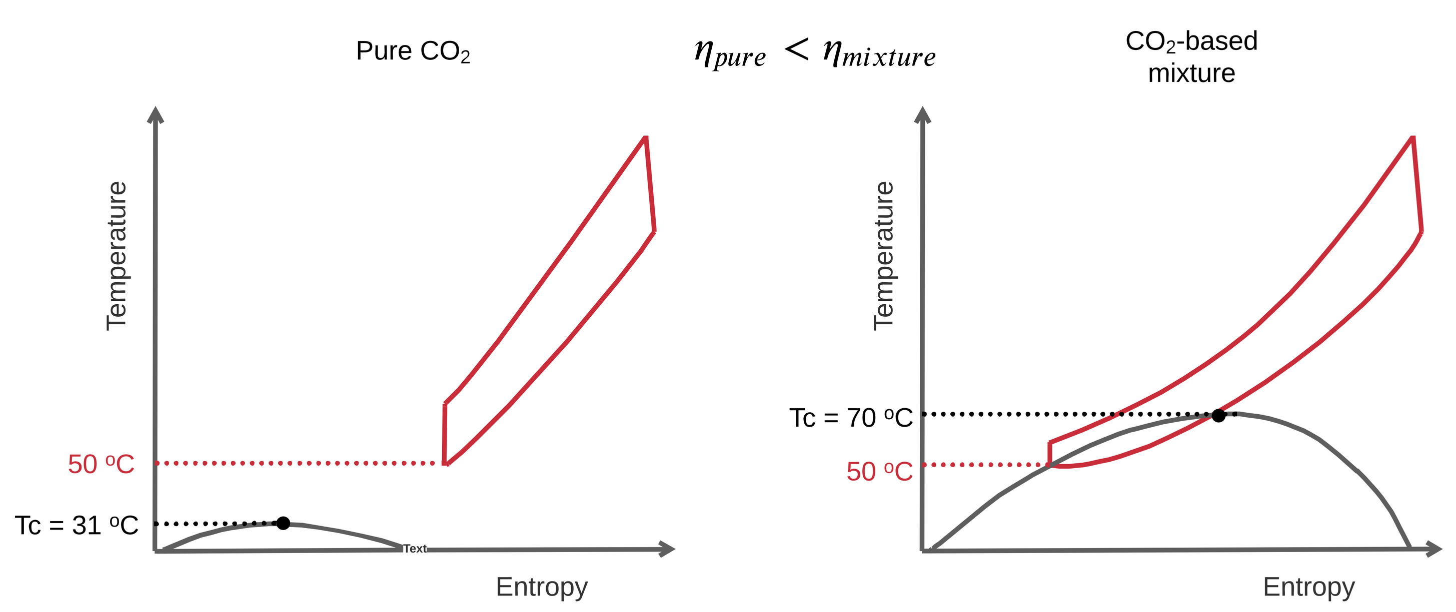
Challenges

CSP built in arid locations do not have access to cooling water, therefore need to depend of ambient air for cooling. This leads to higher compression work and reduced efficiency since the fluid will be compressed at higher temperatures (40 to 50 ºC)

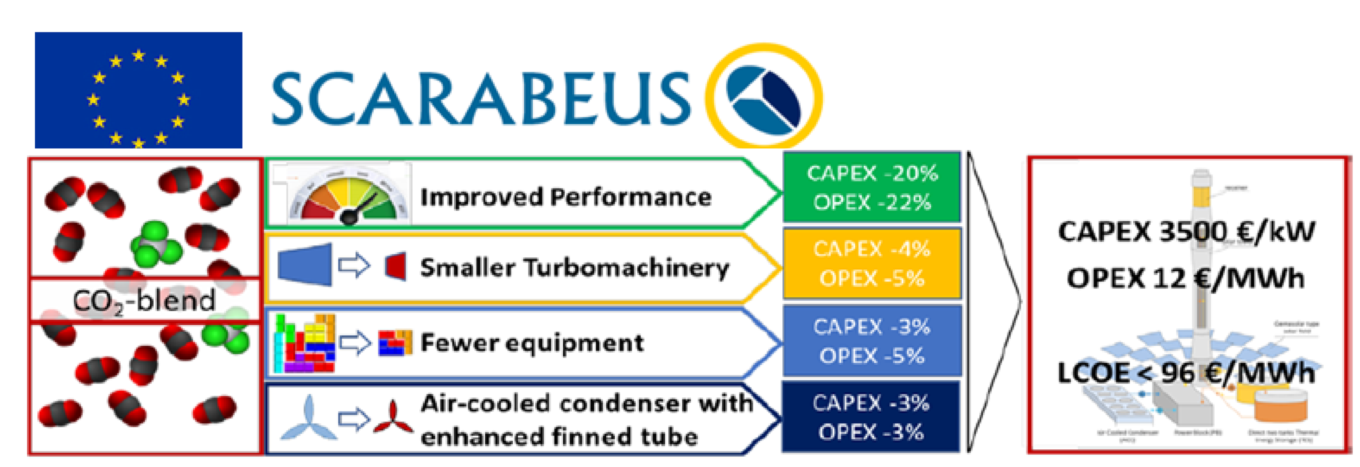


Solution

Increasing the critical temperature of CO_2 by adding impurities (dopants) makes the cycle more compatibe with dry cooling temperatures and allows for working fluid condensation. This reduces compression work and increasing thermal efficiency.

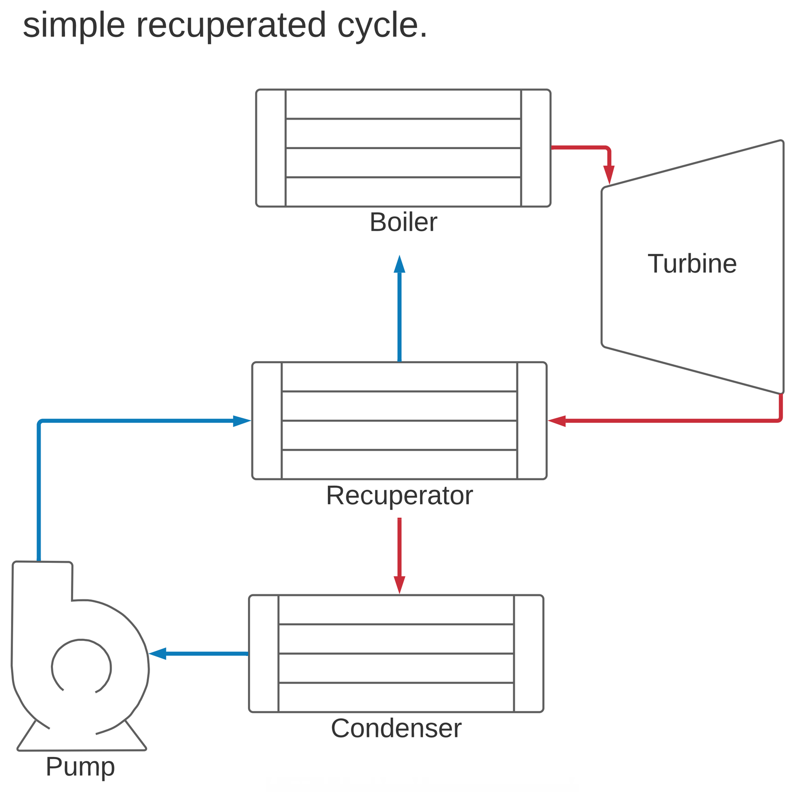


The SCARABEUS project aims to identify the best dopant type and amount that will result in the lowest levelised cost of electricity (LCoE) for CSP plants employing dry cooling.



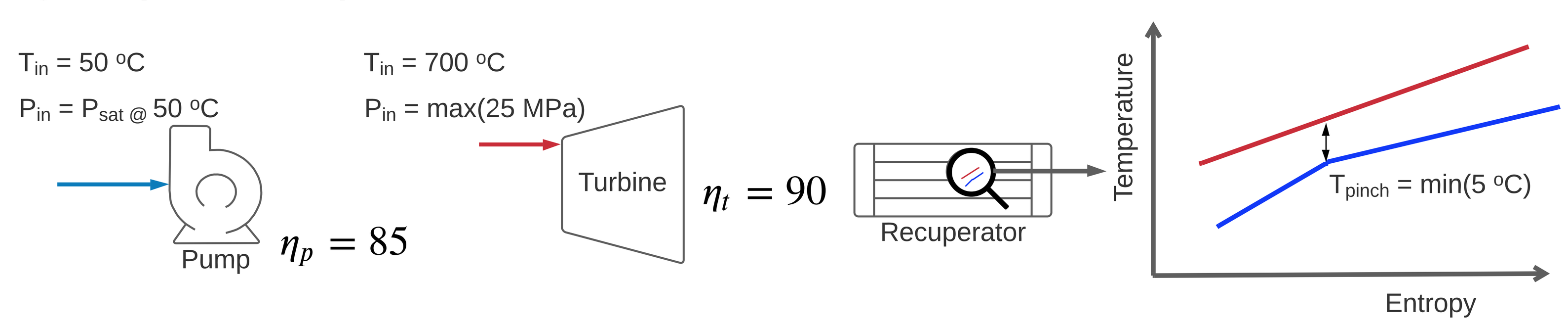
Methodology

A MATLAB code was developed to model a simple recuperated cycle.

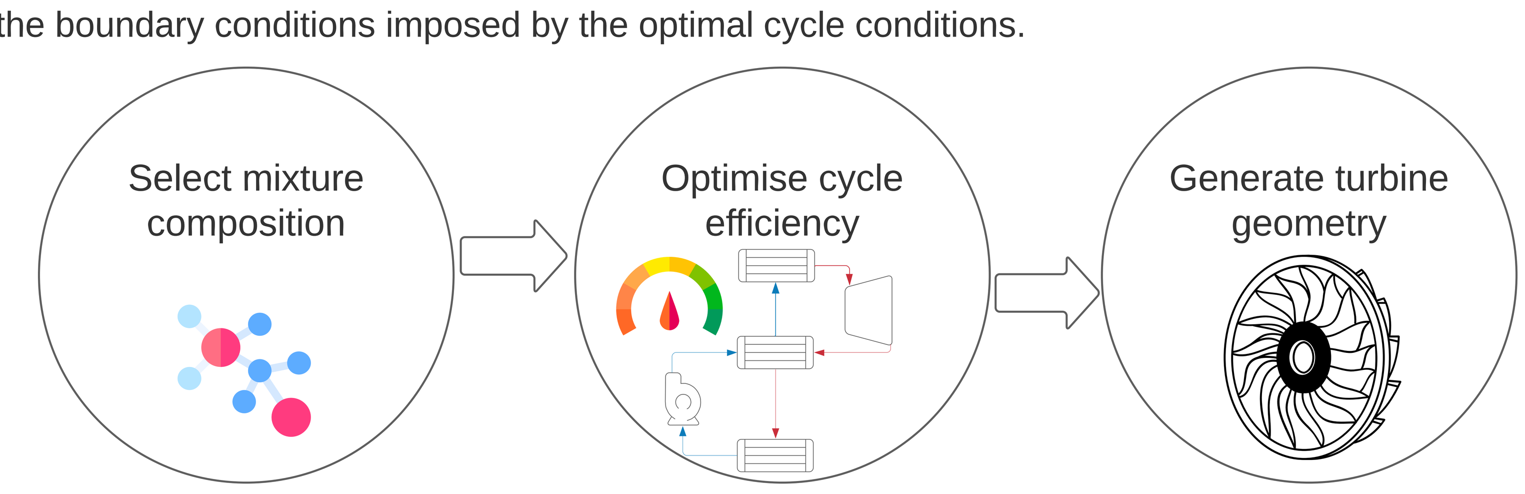


Matlab

Cycle optimisation parameters:



To test the effect of the dopant amount on the cycle and turbine design, the cycle optimisation study is repeated for each dopant molar fraction. A turbine geometry is then generated based on the boundary conditions imposed by the optimal cycle conditions.



A case of **100 MW** capacity power plant was modelled to demonstrate the effect of dopants on a four-stage axial turbine geometry.

Working Fluid modelling:

Three dopants where studied based on recomendations by the SCARABEUS project:

- Titanium tetrachloride (**TiCl4**)
- Sulphur dioxide (**SO2**)
- Hexaflourobenzene (**C6F6**)

A 3rd party software, Simulis Thermodynamics, was employed to model the working fluid and calculate its properties at each point in the cycle. Within Simulis, the Peng-Robinson (PR) equation of state was used in conjunction with the Van der Waals (VdW) mixing rules.

ProSim

PR EoS:

$$P = \frac{RT}{v-b} - \frac{a\alpha}{(v^2+2bv-b^2)}$$

VdW mixing rules:

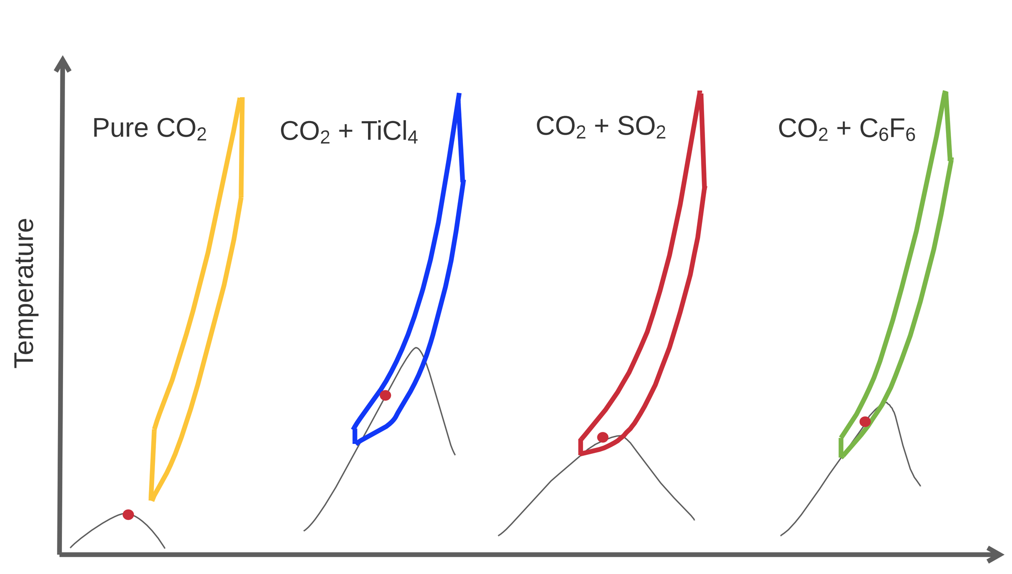
$$a = \Sigma_i^{NC}\Sigma_j^{NC} x_i x_j a_{ij}$$

$$b = \Sigma_i^{NC}\Sigma_j^{NC} x_i x_j b_{ij}$$

Results

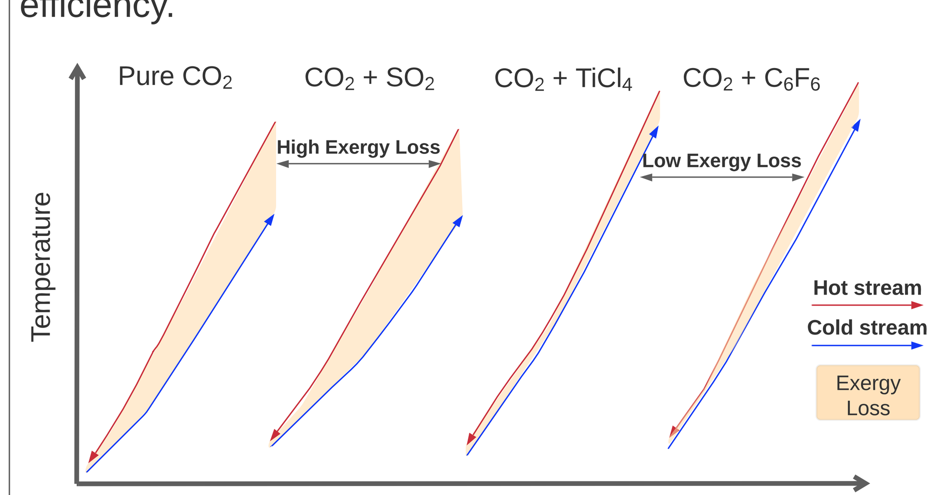
Cycle Analysis:

Working fluid	Dopant molar fraction	Critical temp. (ºC)	Cycle efficiency (%)
Pure CO_2	0	31	41.7
CO_2 + $TiCl_4$	0.174	104	49.5
CO_2 + SO_2	0.264	54	42.3
CO_2 + C_6F_6	0.167	87	46.5

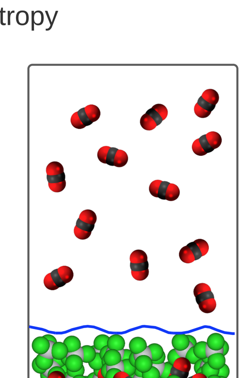


Recuperator Analysis:

Recuperator pinch-point analysis showed that the choice of dopant affects the exergy destruction (irreversibility) during heat exchange. Molecularly complex dopants such as $TiCl_4$ and C_6F_6 reduce irreversibility and increases overall thermal efficiency.

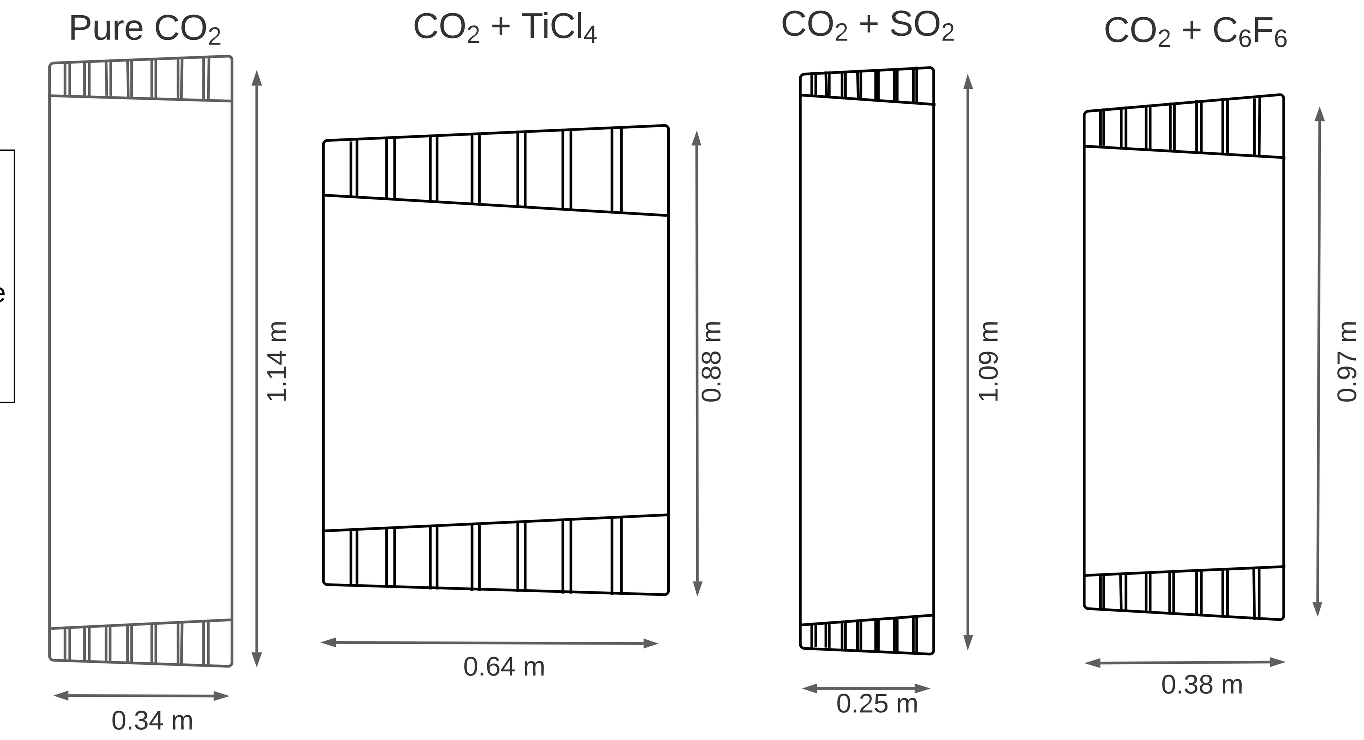


However, the two heavy dopants completly condense whilst CO_2 remains largely in the gas phase - also known as 'fractionation'. This lowers the fluid's heat transfer coefficients and requires larger recuperators.



Turbine Analysis:

Pure CO_2 turbine is used as a baseline for comparison



	CO_2 + $TiCl_4$	CO_2 + SO_2	CO_2 + C_6F_6
	Values compared to pure CO_2 turbine		
Specific work	-52%	-12%	-35%
Mass flow rate	54%	-18%	17%
Volume flow rate	-2%	-27%	-24%
Expansion ratio	-24%	-2%	9%
Mach no.	-14%	-1%	1%
Outlet temperature	6%	0%	7%