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THE 4TH EUROPEAN SCO2 CONFERENCE FOR ENERGY SYSTEMS, 23/03/2021

CLOSED-LOOP SUPERCRITICAL CARBON DIOXIDE WIND TUNNEL: DESIGN AND COMPONENTS

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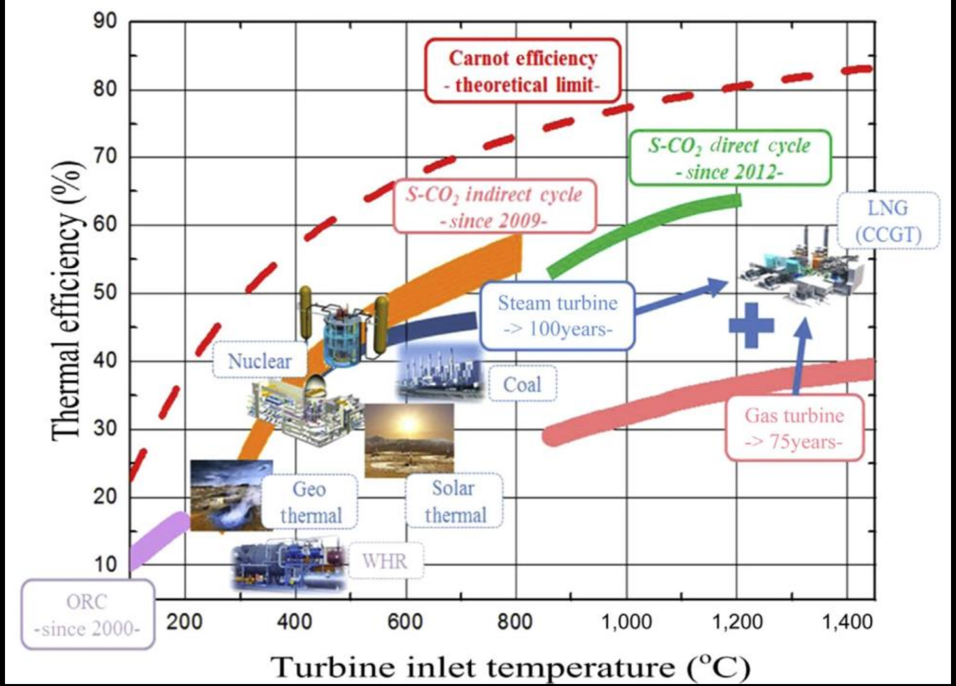
INTRODUCTION

- Compact turbomachines and heat exchangers
- High efficiency
- Low environmental impact
- Suitable for different heat sources ($T_{cr} = 31$°C)
- Higher TIT achievable compared to steam cycles



Ahn, Y., Bae, S.J., Kim, M., Cho, S.K., Baik, S., Lee, J.I. and Cha, H.E. (2015). Review of Supercritical CO2 Power Cycle Technology and Current Status of Research and Development. Nuclear Engineering and Technology, 47(6), pp. 647-661.

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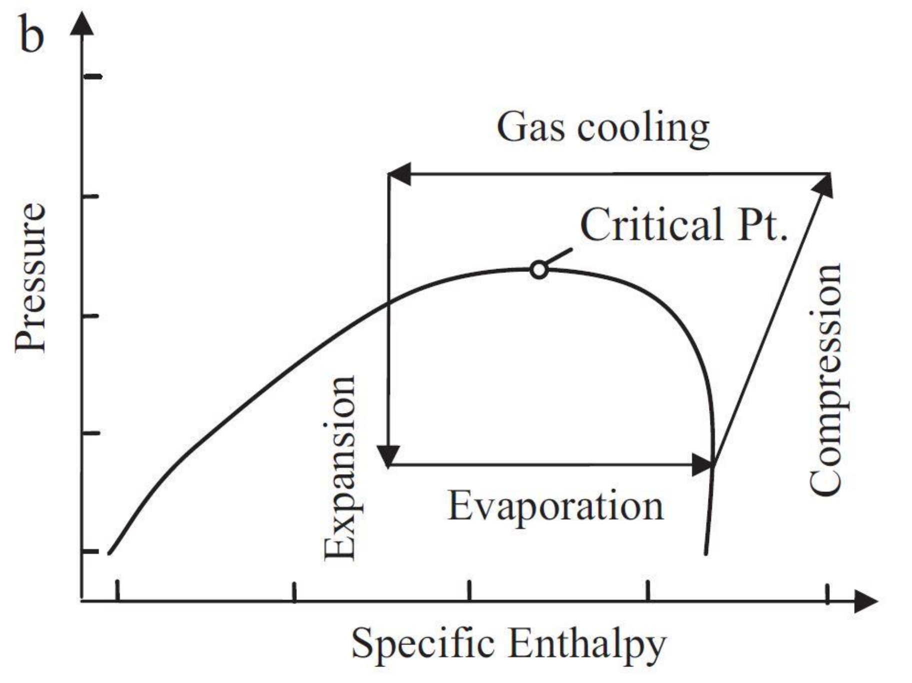
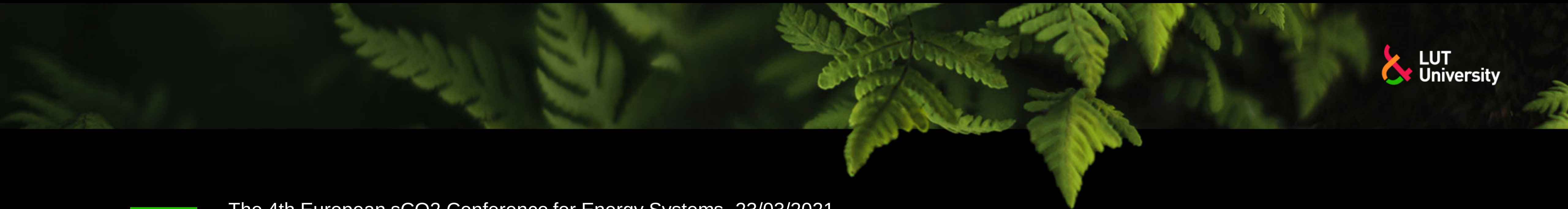
TRANSCRITICAL REFRIGERATION CYCLE

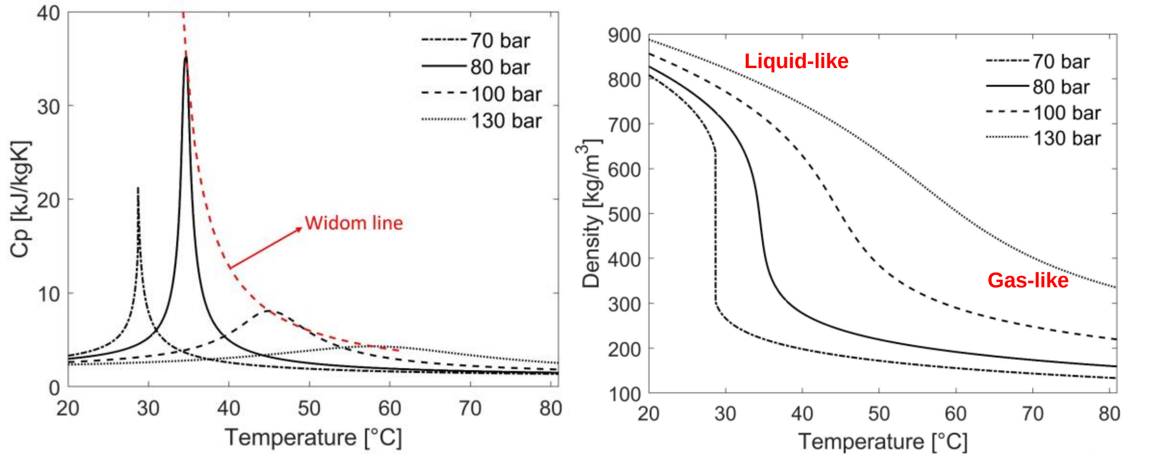
- CO2 is safe (not toxic, flammable or corrosive) and economic
- Alternative to ozone-depleting and global-warming refrigerants
- Possibility of operating with heat rejection temperatures close to the critical point with pressures up to 130 bar
- Technology becoming standardized, costs are strongly decreasing



Austin, B.T. and Sumathy, K. (2011). Transcritical carbon dioxide heat pump systems: A review. Renewable and Sustainable Energy Reviews, 15, pp. 4013-4029.



THERMOPHYSICAL PROPERTIES AND WIDOM LINE



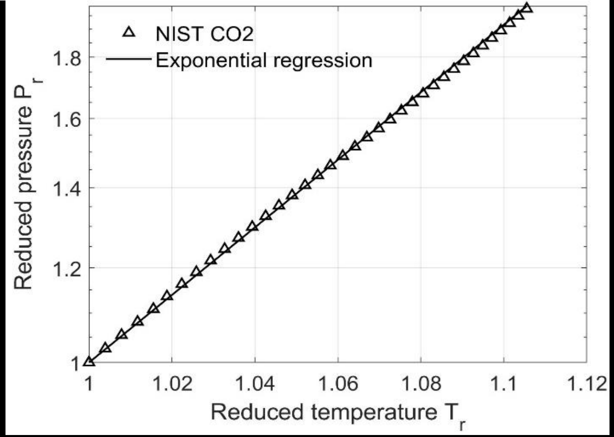
- Sharp variations of the fluid properties in the region near the critical point (31 °C, 73.8 bar)
- Transition from liquid-like to gas-like behaviour crossing the pseudo-boiling temperature at supercritical pressures
- The Widom line is identified by the maxima of the isobaric specific heat:

$$\left(\frac{\partial c_P}{\partial T}\right)_P = \left(\frac{\partial^2 h}{\partial T^2}\right)_P = 0$$

- Banuti (2015) derived an analytical expression for the Widom line of a generic fluid:

$$P_r = \exp[A(T_r - 1)]$$

- The coefficient A is calculated specifically for CO_2 through an exponential regression of the data extrapolated from the NIST REFPROP database $\longrightarrow$ $A = 6.505$



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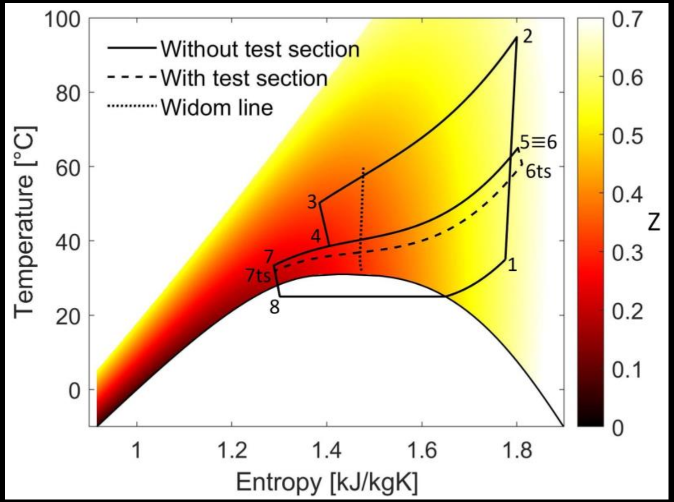
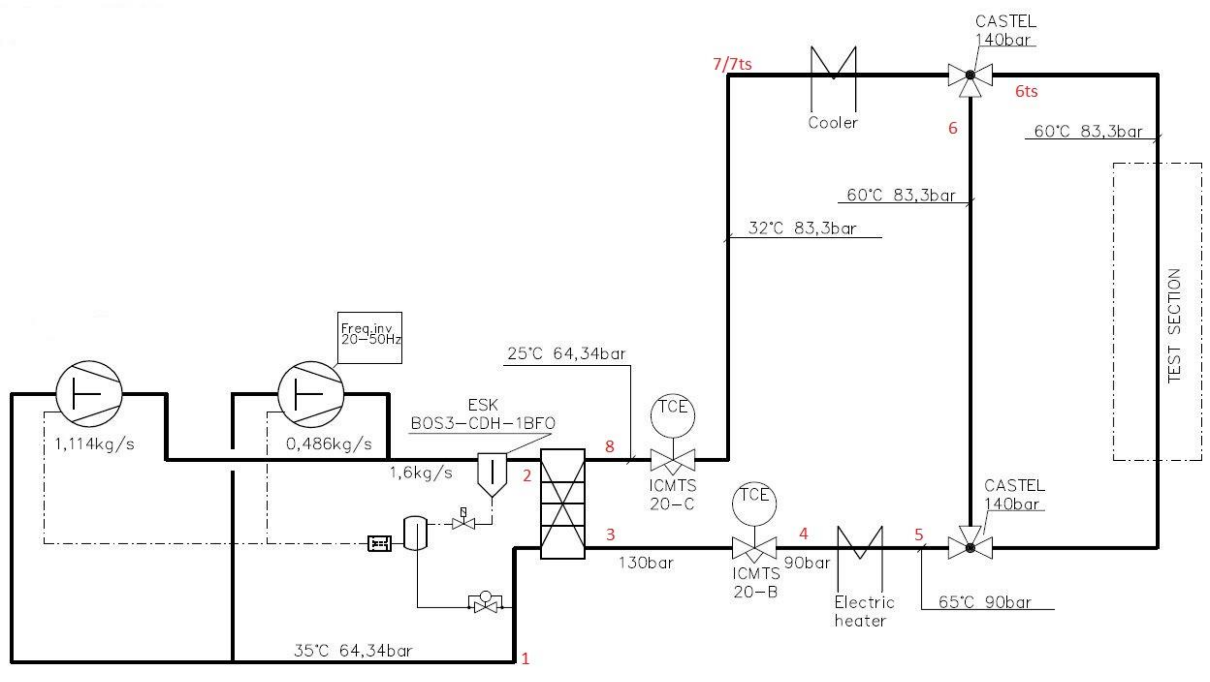
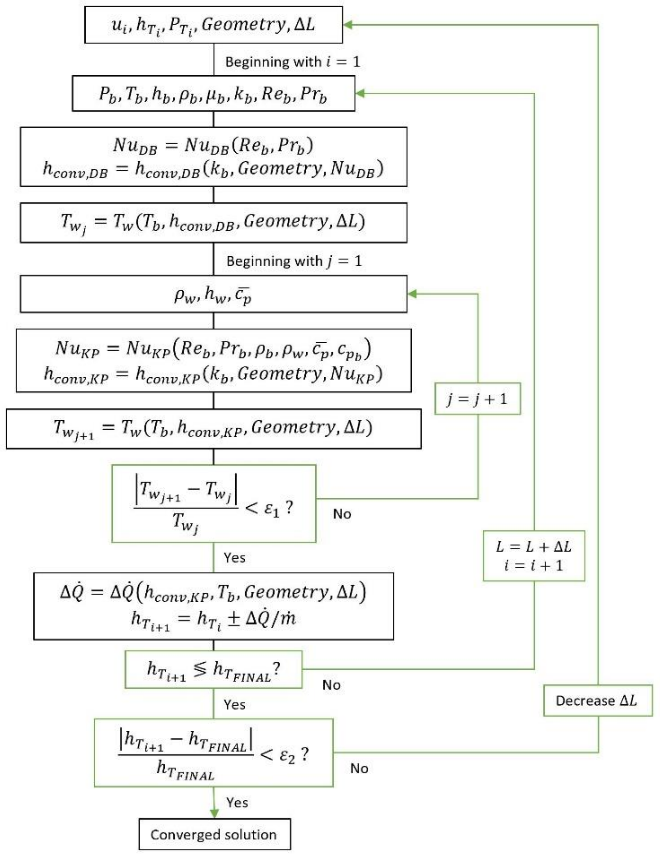
THERMODYNAMIC CYCLE AND LAYOUT

- Constraints on total required power (~500 kW) and dimensions
- Research interests:
  - Heat transfer across the pseudoboiling line
  - Expansion from supercritical condition
  - Non-equilibrium condensation





PRELIMINARY DESIGN OF HEAT EXCHANGERS



- A finite difference method is used to take into account the steep changes in properties across the Widom line
- CO2 properties are calculated from the NIST REFPROP database
- Dittus-Boelter correlation:

$$Nu_{DB} = 0.023\, Re_b^{0.8}\, Pr_b^{m} \qquad \begin{cases} m = 0.3 & \text{Cooling} \\ m = 0.4 & \text{Heating} \end{cases}$$

- Krasnoschekov and Protopopov correlation:

$$Nu_{KP} = 0.0183\, Re_b^{0.82}\, Pr_b^{0.4} \left(\frac{\rho_w}{\rho_b}\right)^{0.3} \left(\frac{\overline{c_p}}{c_{p_b}}\right)^{n}$$

$$n = \begin{cases} 0.4 & for\ T_b < T_w \le T_{pb}\ or\ 1.2T_{pb} \le T_b < T_w \\ 0.4 + 0.2\left(\frac{T_w}{T_{pb}} - 1\right) & for\ T_b \le T_{pb} < T_w \\ 0.4 + 0.2\left(\frac{T_w}{T_{pb}} - 1\right)\left[1 - 5\left(\frac{T_b}{T_{pb}} - 1\right)\right] & \\ \qquad for\ T_{pb} < T_b \le 1.2T_{pb}\ and\ T_b < T_w & \end{cases}$$

$$\overline{c_p} = \frac{1}{T_w - T_b}\int_{T_b}^{T_w} c_p\, dT = \frac{h_w - h_b}{T_w - T_b}$$

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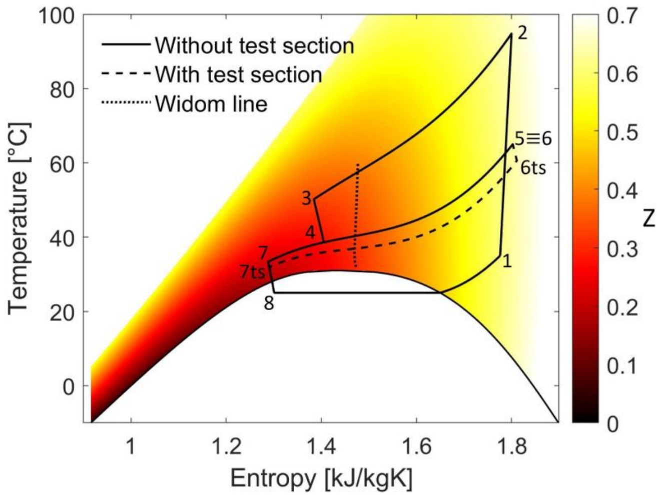
HEATING TEST SECTION

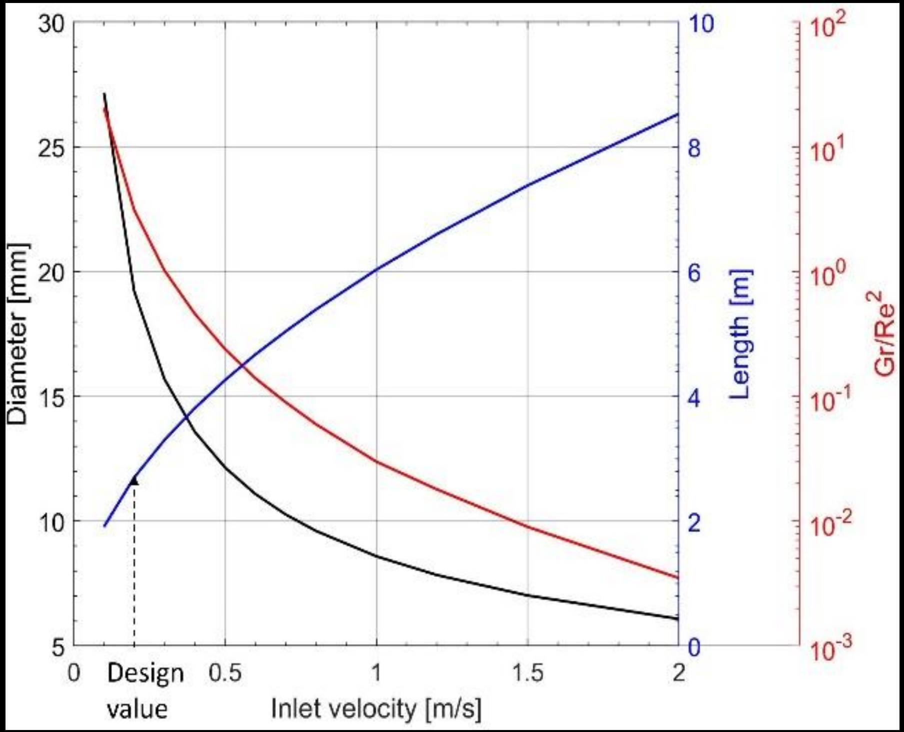
- The flow is split in two parts upstream of the heating test section:
  - 98% of the total is directed to a 200-kW electric circulation heater
  - 2% of the total passes through a uniformly heated pipe equipped with multiple thermocouples

Parameter	Value	Unit
Mass flow rate	0.032	kg/s
Operating pressure	90	bar
Bulk temperature (In – Out)	38.6 – 90	°C
Heat flux	25	kW/m^2
Inlet Reynolds number	$5.27 \cdot 10^4$	-



HEATING TEST SECTION – BUOYANCY EFFECTS

- Large density variations within the fluid → Buoyancy forces
- Grashof number: $$Gr = \frac{g(\rho_b - \rho_w)\rho_b d^3}{\mu^2}$$
- Buoyancy is negligible if: $$\frac{Gr}{Re_b^2} < 10^{-3}$$
- Buoyancy effects are not negligible and therefore the finite difference method previously presented is not applicable



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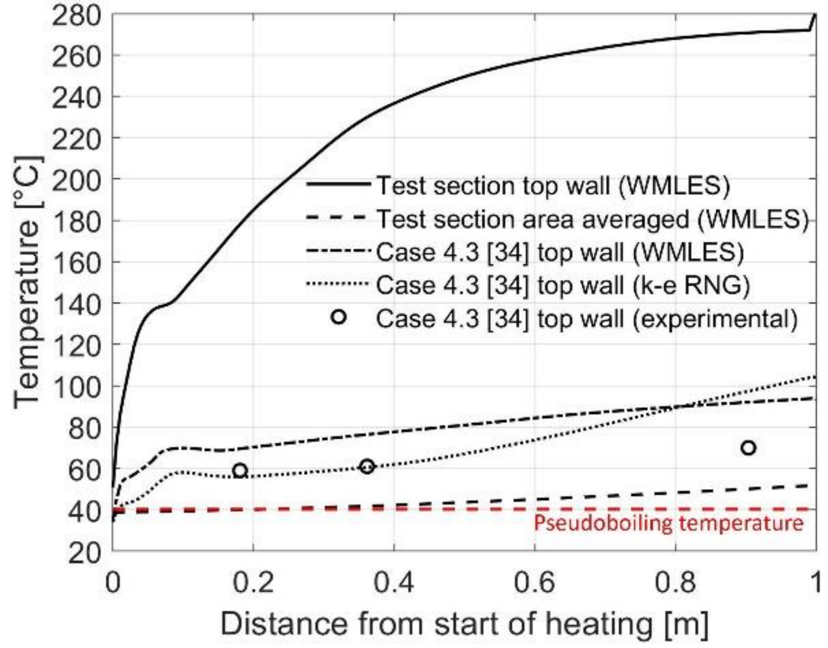
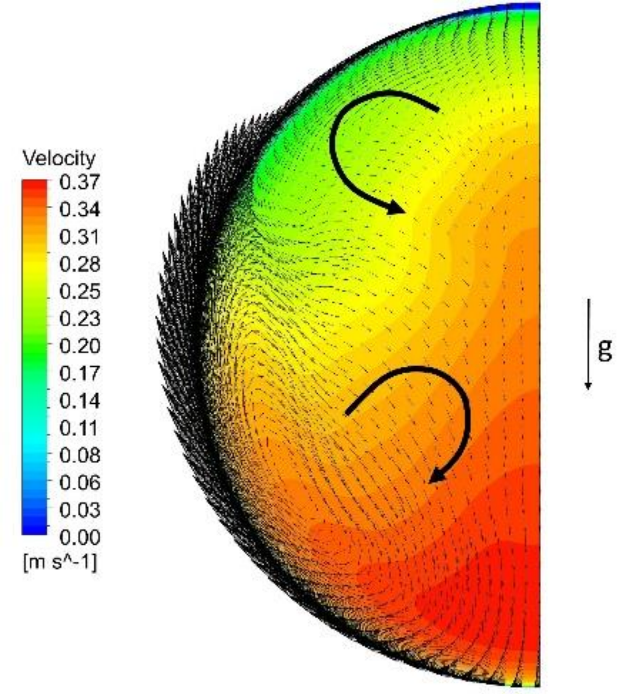
HEATING TEST SECTION – CFD SIMULATION

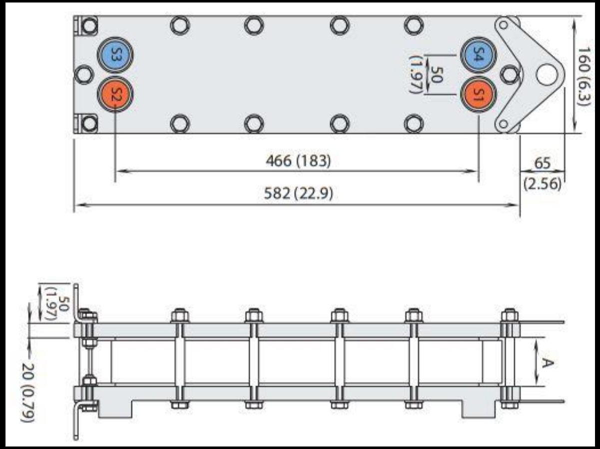


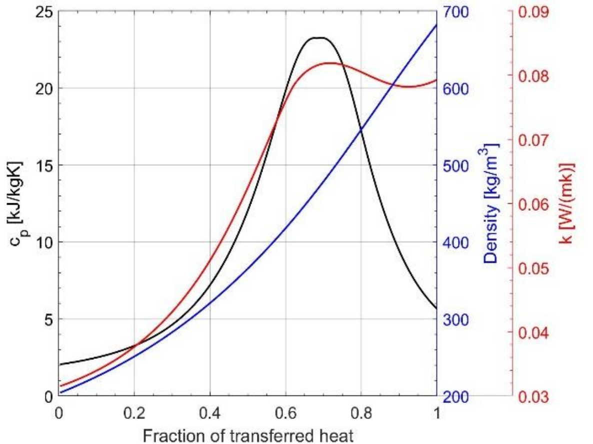


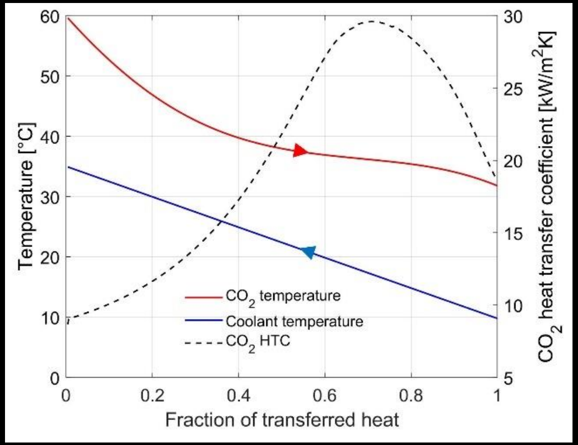
GAS COOLER SELECTION

- Brazed plate heat exchanger (BPHE)
- Able to withstand extremely high operating pressure
- Water used as heat sink

Parameter	Value	Unit
CO_2 temperature (In – Out)	60 – 32	°C
CO_2 operating pressure	83.3	bar
Coolant mass flow rate	2.5	kg/s
Coolant temperatures (In – Out)	10 – 35	°C
Heat exchanged	261	kW

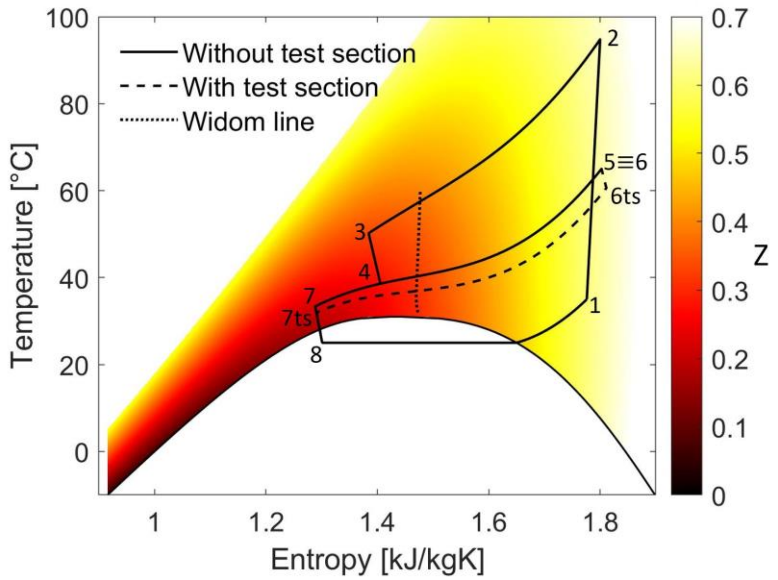




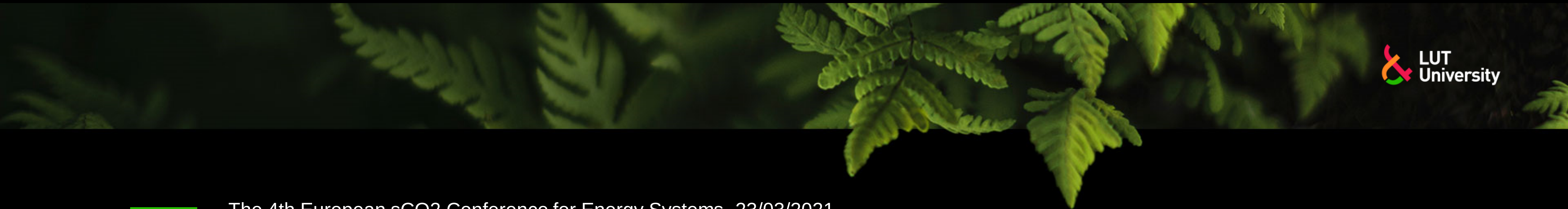


EVAPORATOR SELECTION

- CO$_2$ in both cold ($8 \rightarrow 1$) and hot ($2 \rightarrow 3$) sides
- Trickiest component selection due to high pressure in the hot side CO$_2$
- Possibility of using three smaller brazed plate heat exchangers in parallel



Parameter	Value	Unit
Hot side temperature (In – Out)	94.8 – 50.2	°C
Hot side operating pressure	130	bar
Cold side temperature (In – Out)	24.9 – 34.7	kg/s
Cold side operating pressure	64.3	°C
Heat exchanged	227	kW



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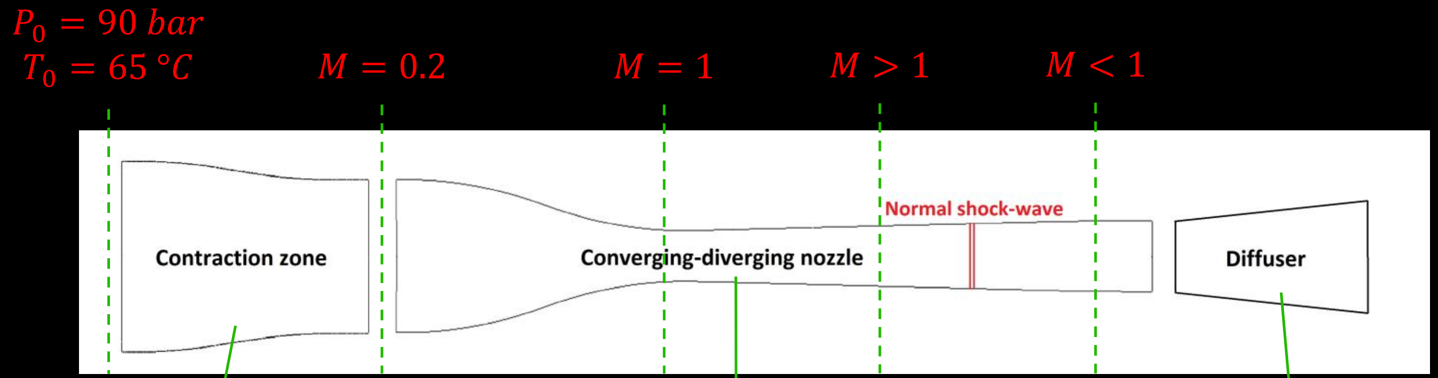
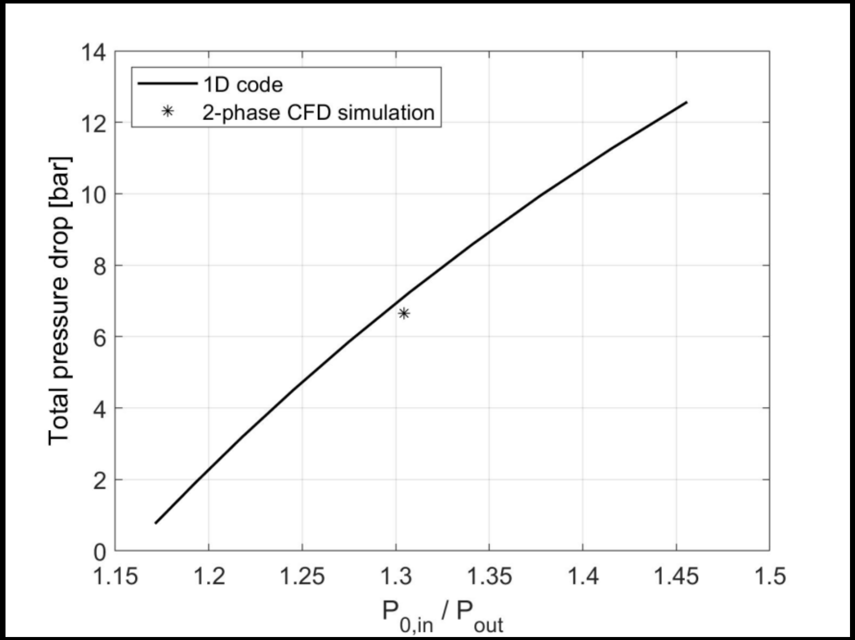
SUPERSONIC TEST SECTION



Transition from circular to rectangular cross-section

Supersonic expansion and condensation

Recovery of the kinetic energy



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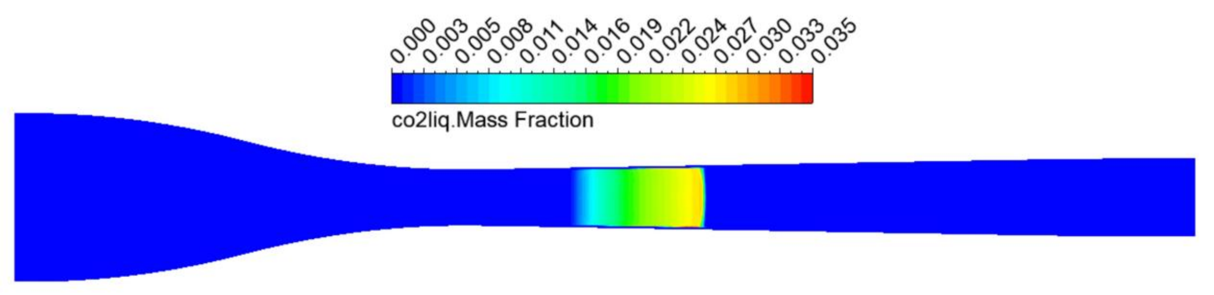
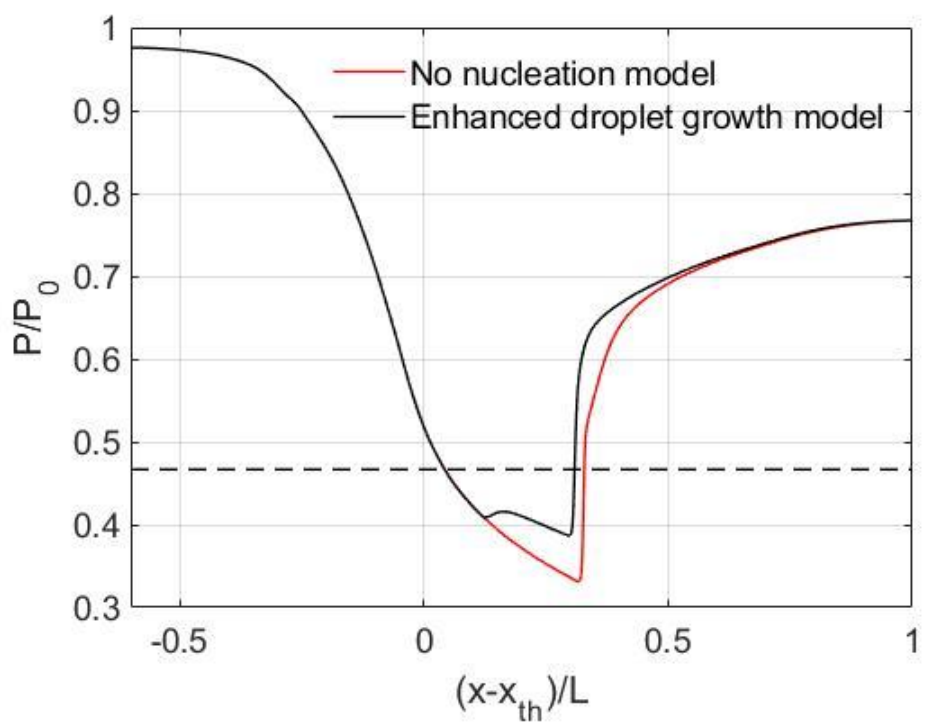
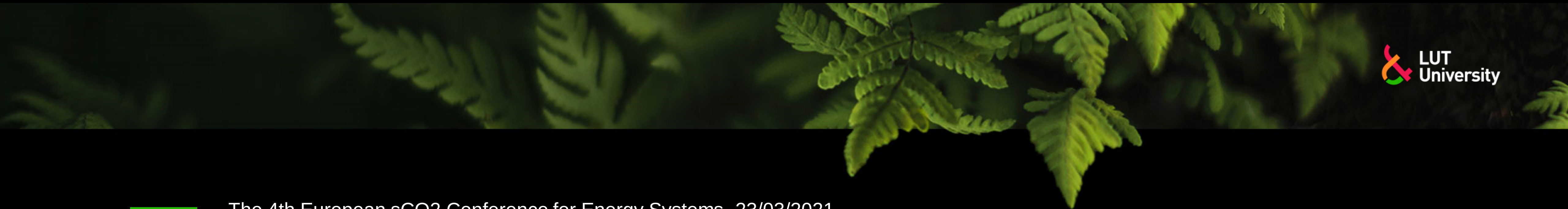
SUPERSONIC TEST SECTION – CFD SIMULATION

- A real-gas two-phase CFD simulation of the supersonic test section in design operating conditions was run
- Non-equilibrium condensation is triggered in the divergent part of the nozzle once that the Wilson point is reached
- Simultaneously with the droplets growth, pressure and temperature tend to return to saturated conditions







CONCLUSIONS AND FUTURE WORK

- The sCO2 experimental test loop is presented. The latter allows to study relevant phenomena occurring in the supercritical region, specifically related to heat transfer in proximity of the Widom line and to expansions in the non-ideal gas region and two-phase region. The loop is under commissioning.
- Preliminary design and selection of the heat exchangers was carried out. Buoyancy effects greatly influences the flow field and heat transfer in the heating test section.
- A real-gas CFD simulation was run to assess qualitatively the temperature profiles along the heater walls. The choice of the turbulence model is of fundamental importance to capture the flow features and perform accurate predictions of the heat transfer.
- The supersonic test section was simulated through a real-gas two-phase CFD simulation. The results confirm that nucleation of droplets is triggered in the divergent section of the nozzle.
- Future research will focus on design of the control and measurement systems, as well as assessment of more accurate numerical models to describe the CO_2 behaviour in the supercritical region.

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