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DESIGN OF A CLOSED LOOP SCO2 WIND TUNNEL: NUMERICAL MODELLING OF NON-EQUILIBRIUM CONDENSATION IN A CONVERGING-DIVERGING NOZZLE

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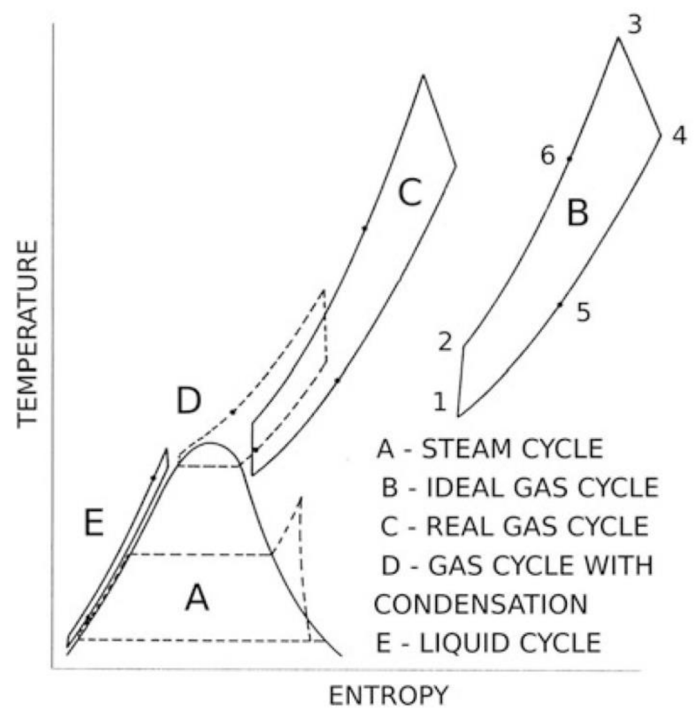
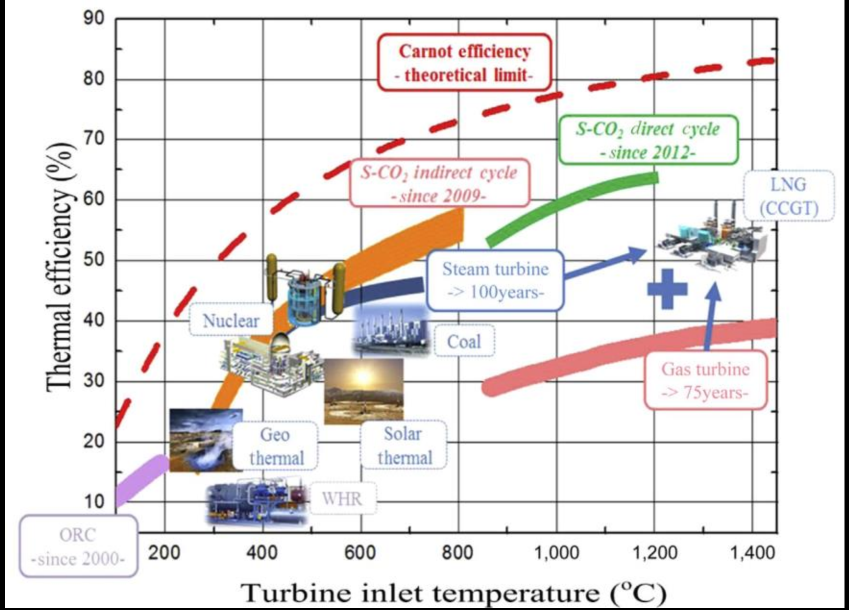
CONTENTS

S-CO2 APPLICATIONS AND POWER CYCLES

- sCO2 is compressed in the near-incompressible region (cycles C and D)
- Compactness and high efficiencies
- Suitable for different heat sources ($T_{cr} = 31°\mathrm{C}$)
- Higher TIT achievable compared to steam cycles



(Invernizzi, 2013)



(Ahn et Al., 2015)

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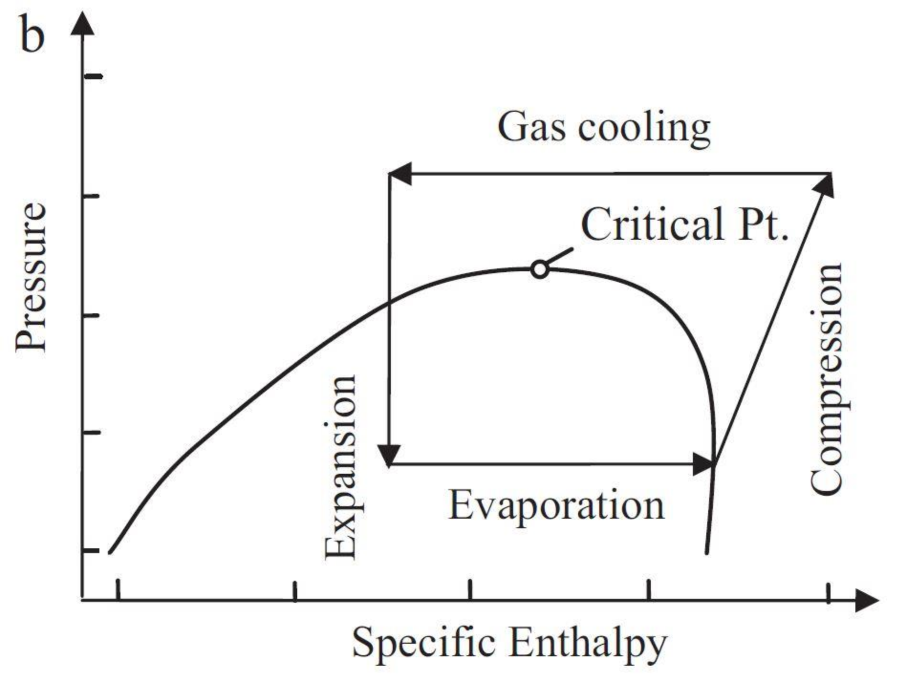
TRANSCRITICAL REFRIGERATION CYCLE

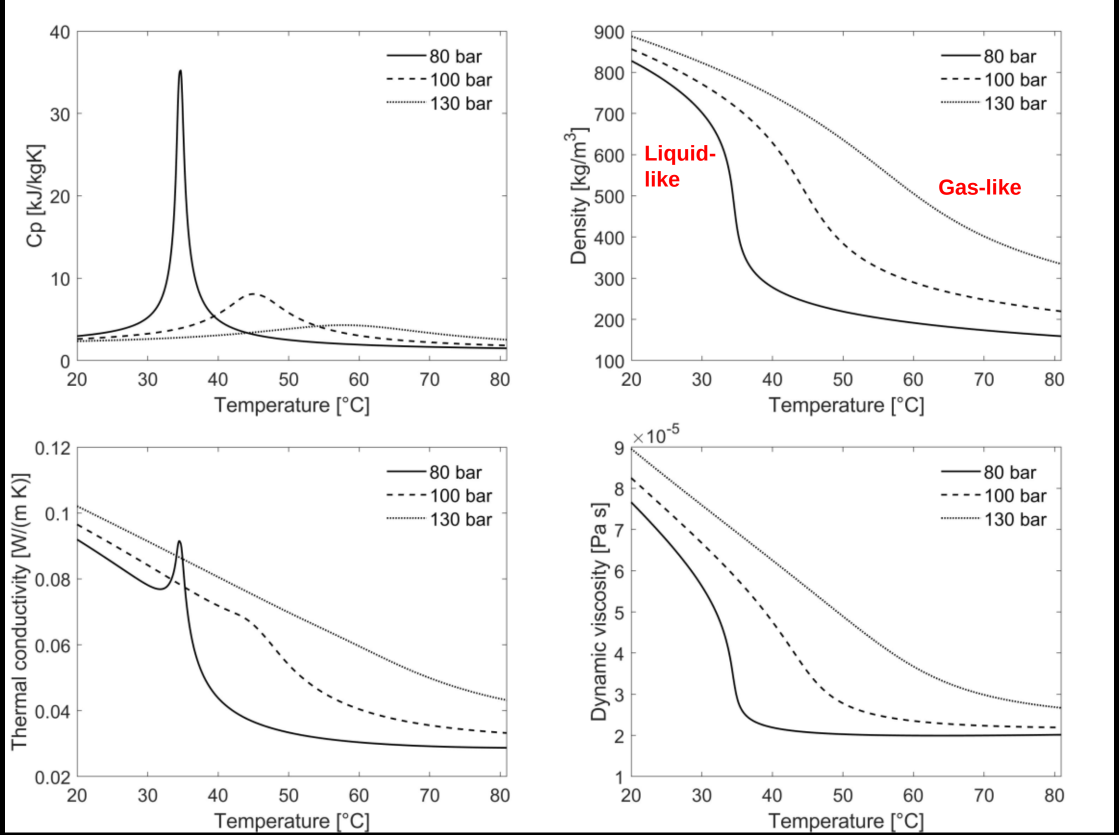
- CO2 is safe (not toxic, flammable or corrosive) and economic
- Alternative to ozone-depleting and global-warming refrigerants
- Possibility of operating with heat rejection temperatures close to the critical point with pressures up to 130 bar
- Technology becoming standardized, costs are strongly decreasing



(Austin et Al., 2011)

THERMOPHYSICAL PROPERTIES

- Compressibility factor: $Z = \frac{P}{\rho R T}$
- Real-gas behaviour of the fluid in the supercritical region ($Z = 0.2 \div 0.5$)
- 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



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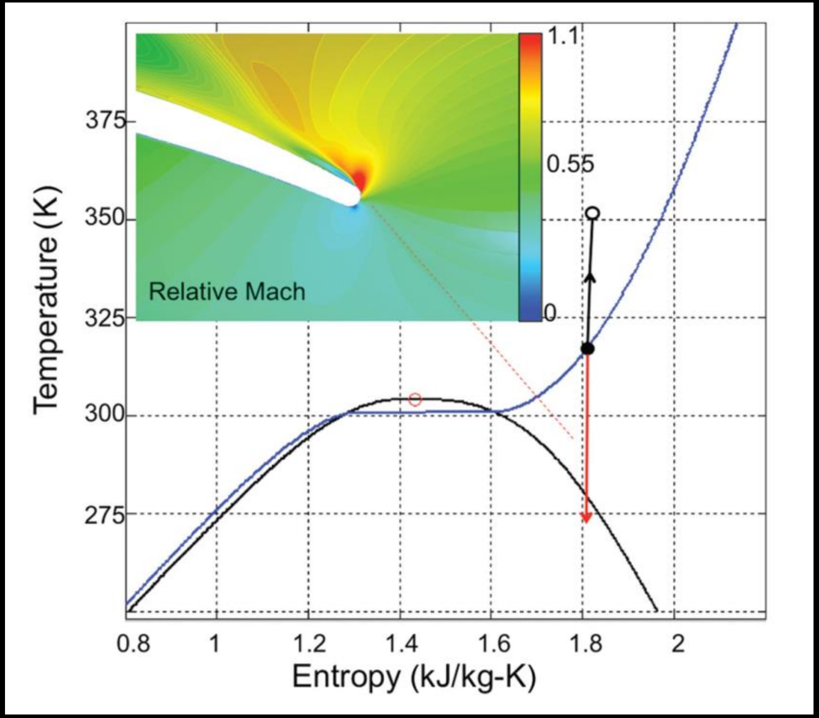
POSSIBLE CONDENSATION IN COMPRESSORS

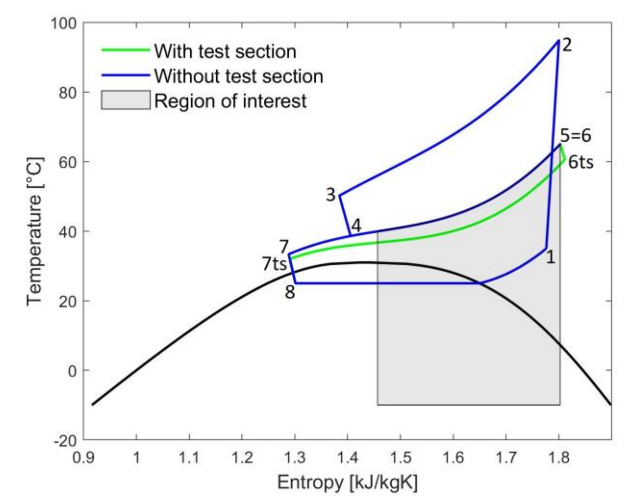
- Flow acceleration on the suction side of the compressor blade may cause the nucleation of liquid droplets
- Condensation would affect the performance of the machine
- Lettieri et al. defined a criterion to determine a limit for condensation-free inlet conditions of compressors

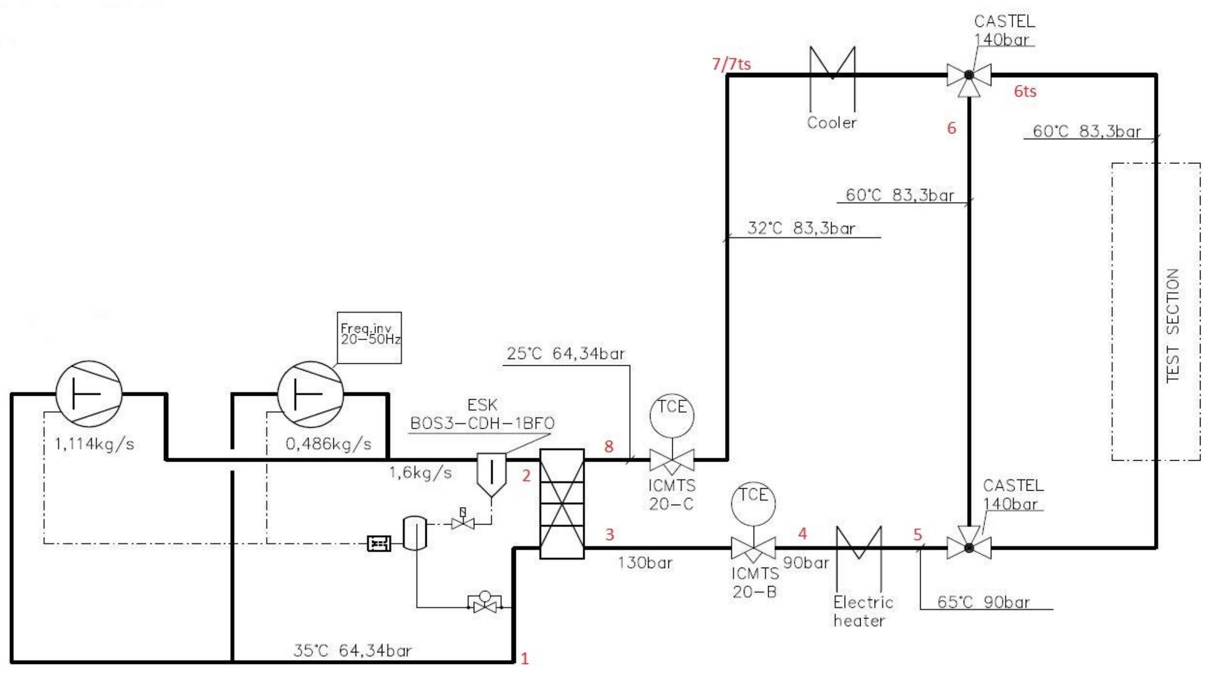


(Baltadjiev et Al, 2015)

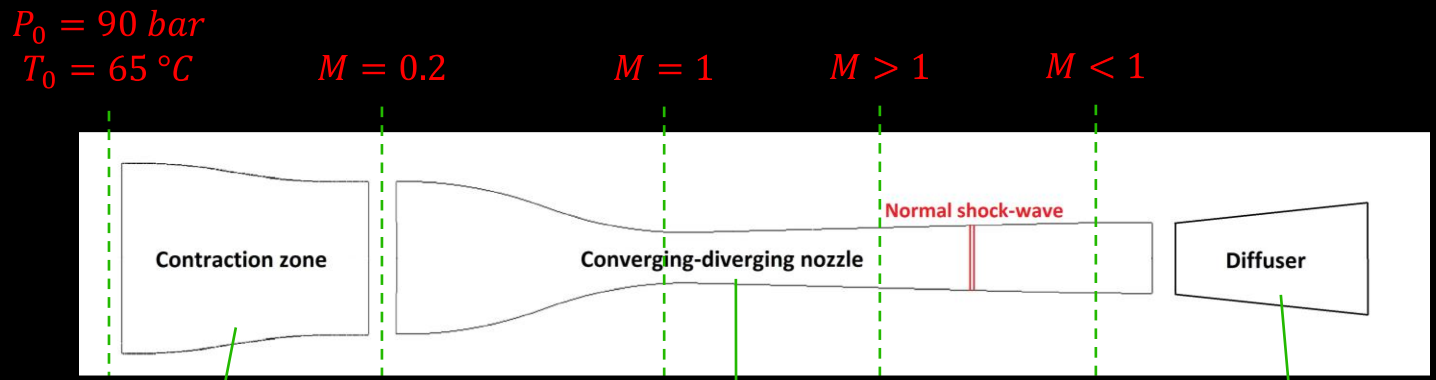
THERMODYNAMIC CYCLE AND LAYOUT

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





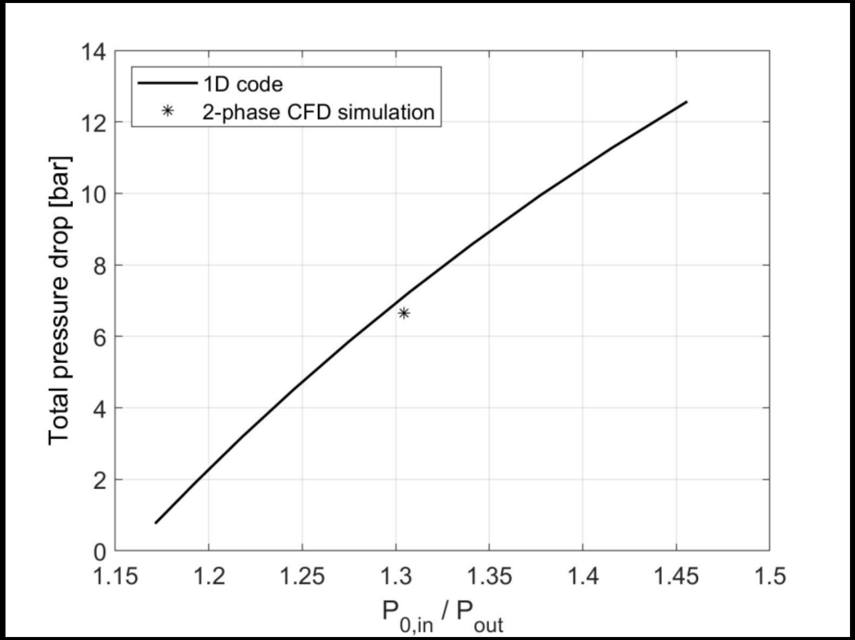
SUPERSONIC TEST SECTION



Transition from circular to rectangular cross-section

Supersonic expansion and condensation

Recovery of the kinetic energy



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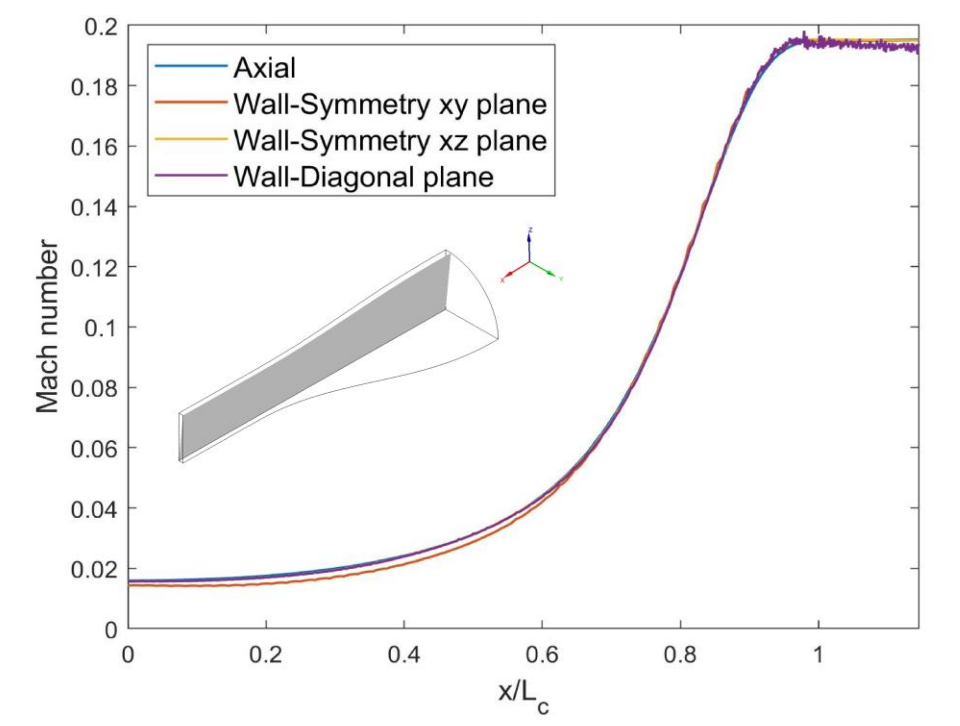
CONTRACTION ZONE: CFD RESULTS

- Real-gas CFD simulation carried out in Ansys Fluent
- Unstructured mesh with ICEM CFD
- Total pressure loss coefficient:

$$Y = \frac{P_{0,in} - P_{0,out}}{P_{0,out} - P_{out}} = \begin{cases} 0.0004 & \text{Inviscid} \\ 0.0348 & \text{Viscous} \end{cases}$$



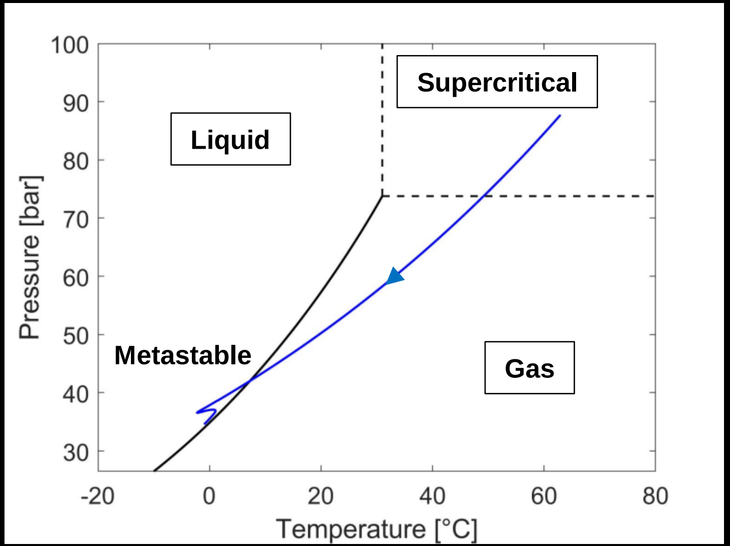
NON-EQUILIBRIUM CONDENSATION MODEL

Droplets nucleation rate: $J = \frac{1}{1+\theta}\frac{\rho_g^2}{\rho_l}\sqrt{\frac{2\sigma}{\pi M^3}}\cdot\exp\left(-\frac{4\pi r^{*2}\sigma}{3k_B T_g}\right)$

Critical radius: $r^* = \frac{2\sigma}{\rho_l R T_g \int_{P_s}^{P}\frac{Z}{P}dP} = \frac{2\sigma}{\rho_l R T_g\left[\ln S + A(P_s)\cdot P_s(S-1)\right]}$

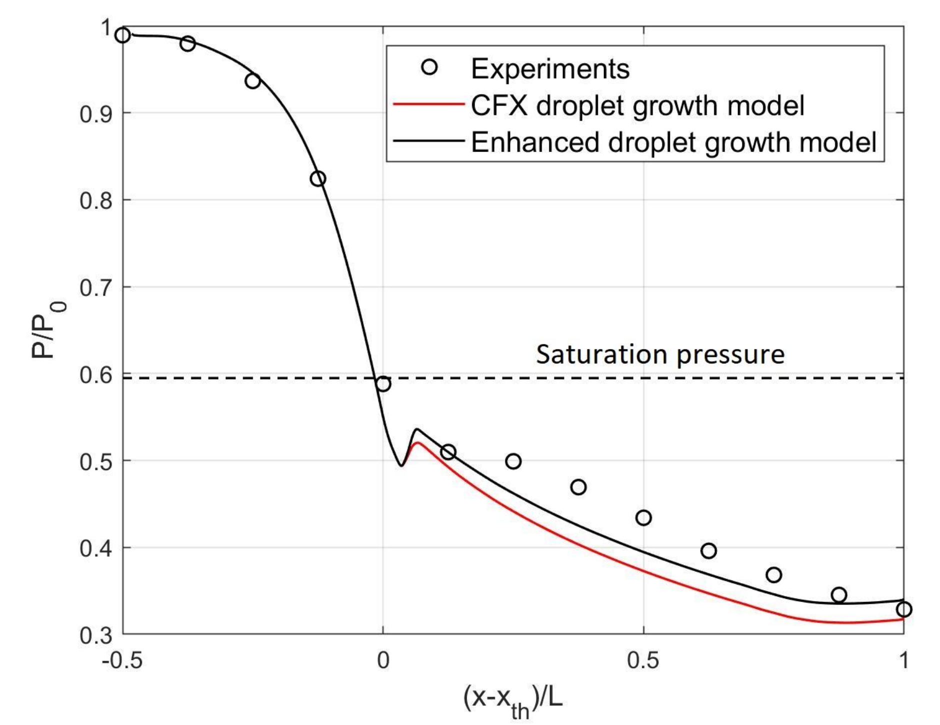
Droplet growth rate model: $\frac{dr}{dt} = \frac{k_g}{r\rho_l\left[\frac{1}{1+4Kn}+3.78(1-\nu)\frac{Kn}{Pr_g}\right]}\left(\frac{T_l-T_g}{L}\right)$

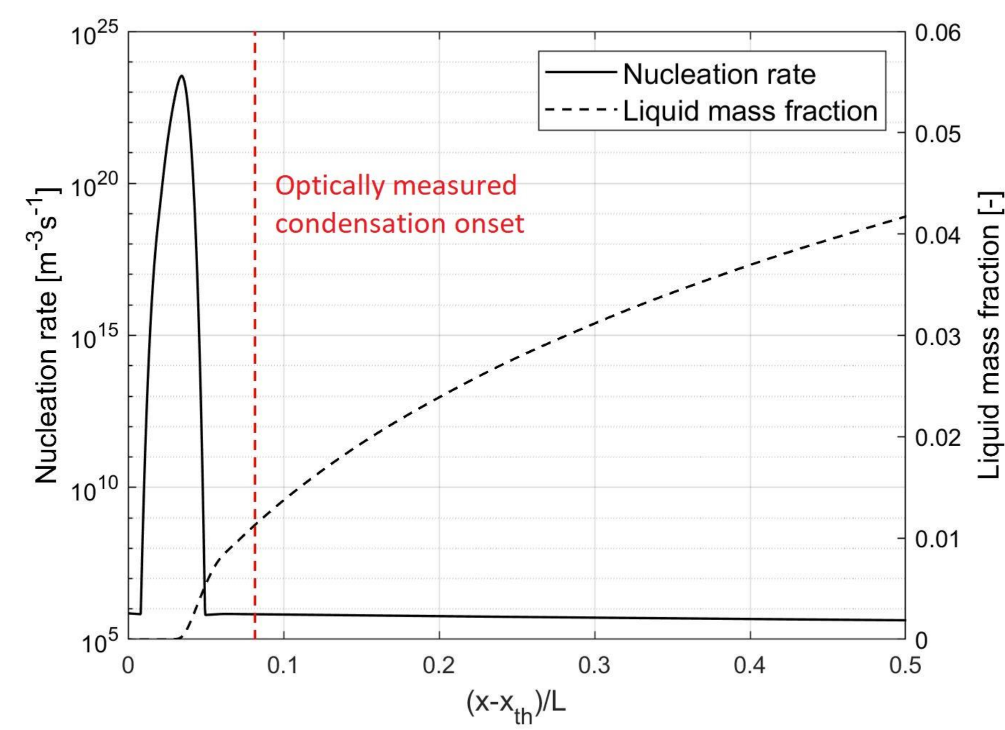
$$T_l = T_s(P) - \left[T_s(P) - T_g\right]\frac{r^*}{r}$$



θ	Non-isothermal correction term
σ	Surface tension
M	Molecular mass
k_B	Boltzmann constant
S	Supersaturation ratio
ν	Young modification parameter
Kn	Knudsen number
Pr	Prandtl number

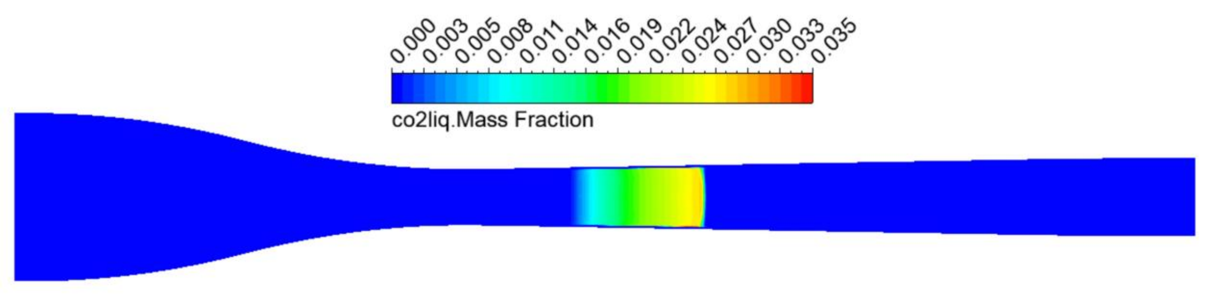
VALIDATION OF THE CONDENSATION MODEL

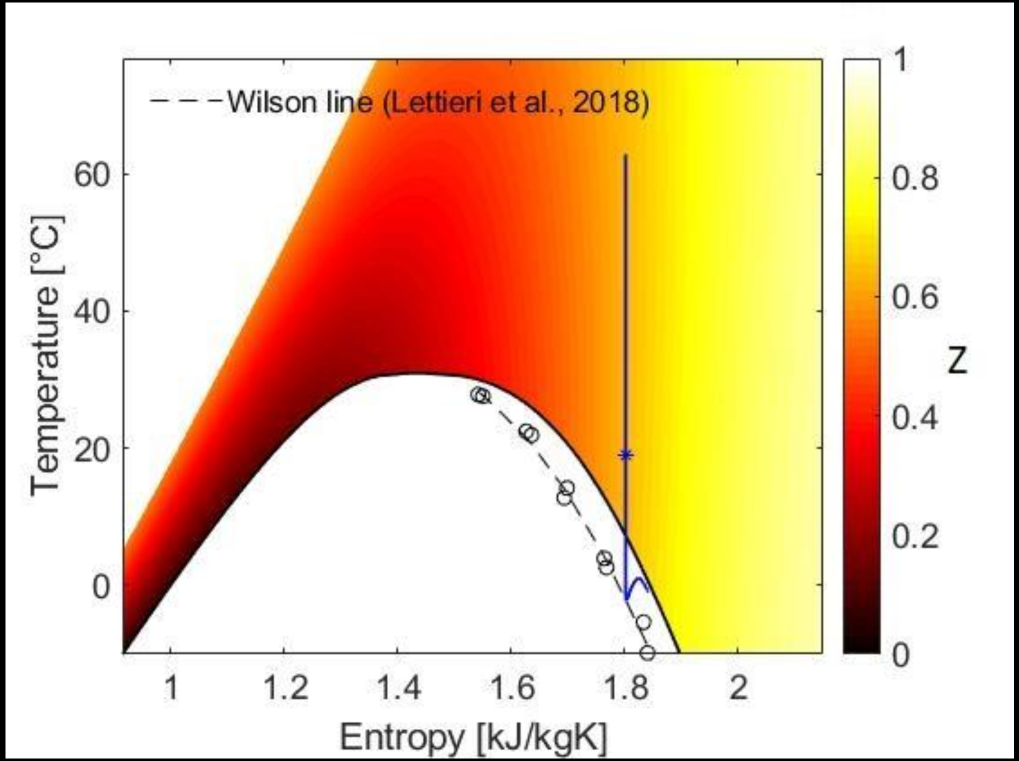




DESIGNED NOZZLE: EXPANSION AND CONDENSATION

- Expansion rate: $\dot{p} = -\frac{w}{p}\frac{dp}{dx}$
- Average value of $2.1 \cdot 10^3\ s^{-1}$ within the metastable region
- Pressure and temperature return to saturated conditions once that the Wilson line is reached





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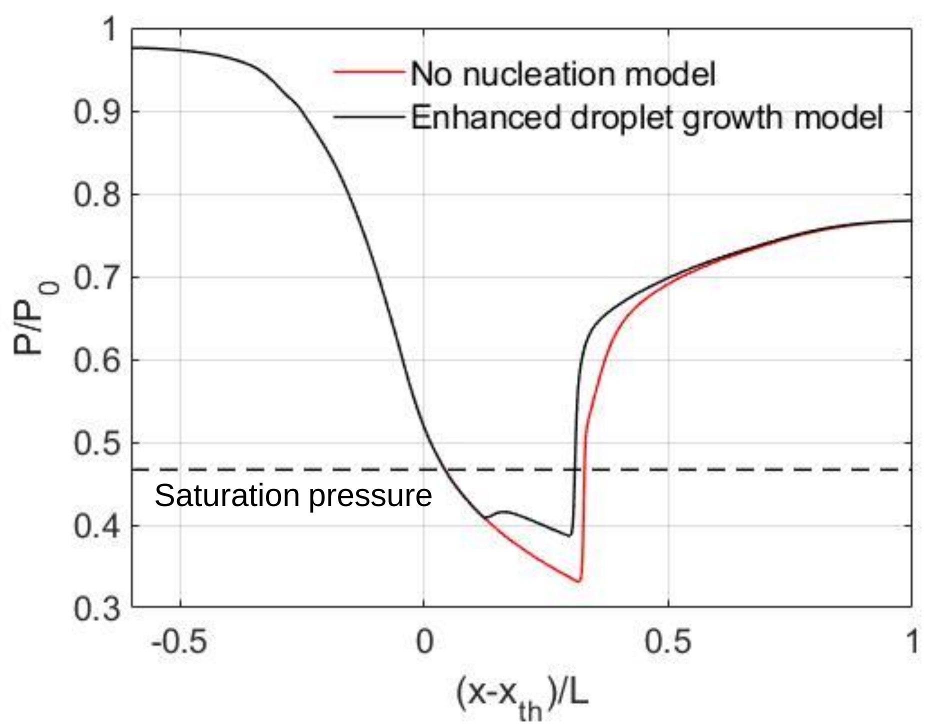
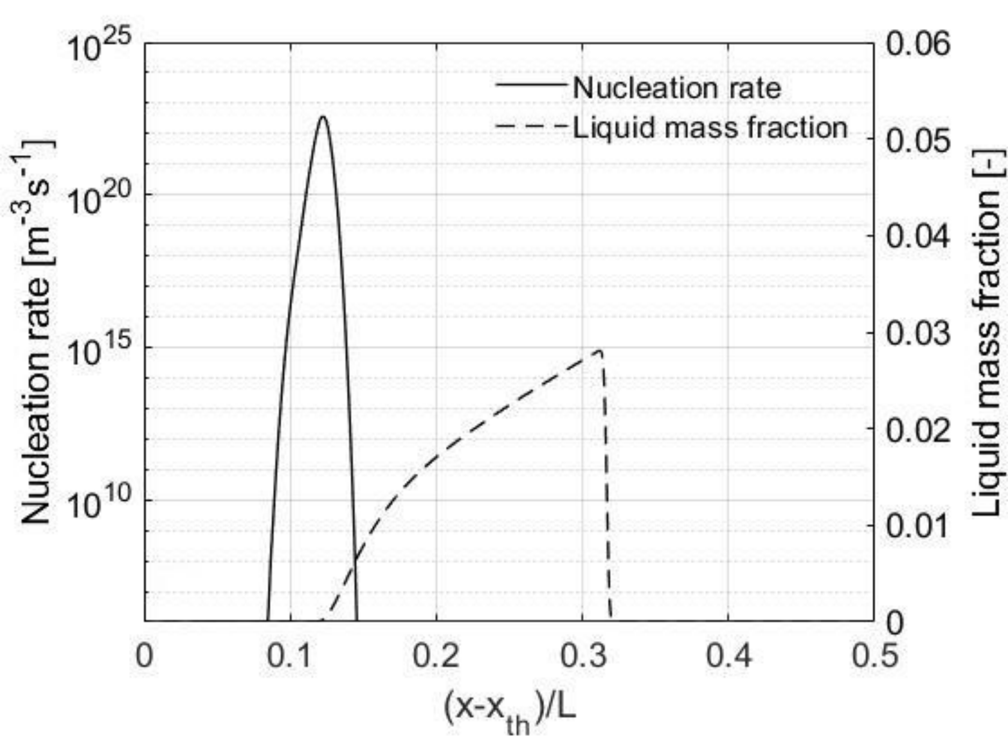
DESIGNED NOZZLE: CFD RESULTS





CONCLUSIONS AND FUTURE WORK

- The sCO2 experimental test loop, which will allow the study of relevant phenomena taking place in the non-ideal gas region, is presented. The loop is under commissioning.
- The results from the real-gas CFD simulation of the contraction zone indicate that no flow separation occurs, and a two-dimensional flow is provided to the supersonic test section.
- The presented condensation model is validated and applied to the designed nozzle. The model assume a linear relation between the compressibility factor and pressure around the saturation pressure.
- The effects of the low surface tension on condensation can be further studied and new condensation models can be developed considering the gas as non-ideal, i.e. compressibility factor lower than 1.

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DESIGNED NOZZLE: CFD RESULTS