Supercritical CO$_2$ Heat Transfer away from pseudocritical temperature: Influence of buoyancy

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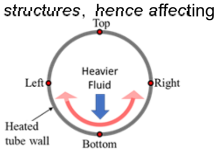
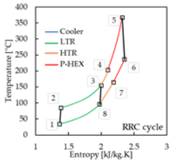
OBJECTIVES

- Near the thermodynamic critical point, effects of buoyancy on sCO$_2$ internal convection heat transfer has been reported by many authors.
- For sCO$_2$ flows through tubes with heated surfaces, temperature difference between wall and bulk flow at can cause variation in density.
- This can generate buoyancy forces, affect turbulence generation in the flow, and create secondary flow structures, hence affecting convection heat transfern

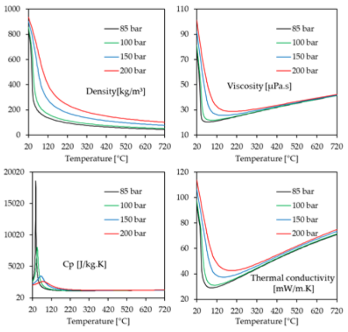


Schematic showing formation of natural convection currents in a cross section of a heated circular tube



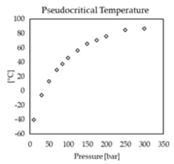
T-s diagram of an sCO$_2$ RRC cycle

- ***Why is heat transfer away from pseudocritical temperatures important?***
- Heat exchangers and recuperators in an sCO$_2$ cycle operate away from pseudrocritical temperatures
- Especially critical for shell-and-tube type of recuperators with macro-sized tubes where effects of buoyancy are more probable
- Can be applied to design of turbine blade internal cooling passages



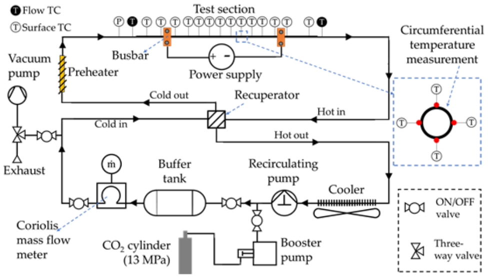
Property variation for CO$_2$ with pressure and temperature plotted using CoolProp NIST tables

- Non-linear variation in CO$_2$ properties still exists until 300°C for 200 bar pressure.
- It is interesting to study effects of such property behavior on heat transfer for better design of heat exchangers and recuperators
- ***Presented study includes heat transfer results for 10-300 bar pressure and 100-465°C temperature***



Pseudocritical temperature at different pressure for CO$_2$

EXPERIMENTAL METHODOLOGY

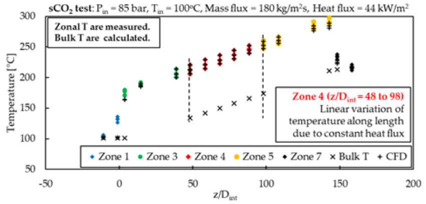


Schematic of closed loop sCO$_2$ heat transfer testing setup

- Pressure range = 80-200 bar, temperature up to 700°C for Inconel and 510°C for stainless steel

NUMERICAL METHODOLOGY

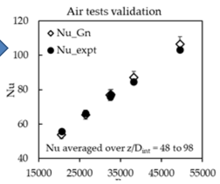
- Conjugate heat transfer RANS CFD in Fluent with the NIST Real Gas model tables
- K-omega SST turbulence model with wall $y^+<1$
- Mesh independence study is also performed



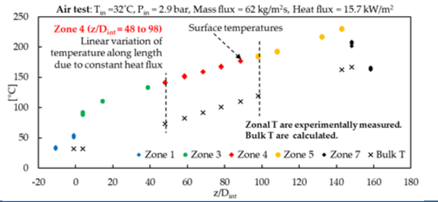
Comparison of measured and CFD external wall temperatures for the entire test section for a sCO$_2$ test

AIR VALIDATION RESULTS

Heat transfer validation results using air (Error bars shown are 4% of Gnielinsky Nusselt number)

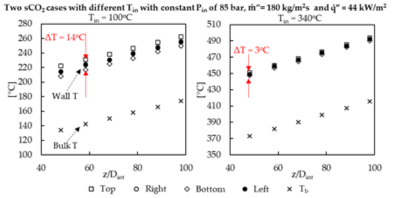


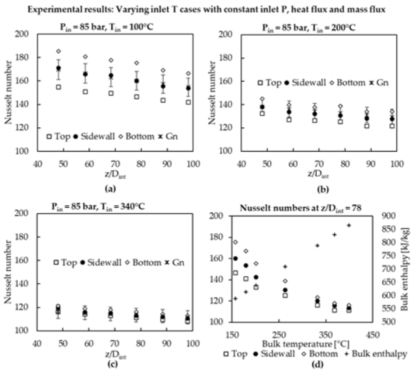
Variation of surface temperatures in different zones and calculated bulk temperatures for the entire test section for an air test



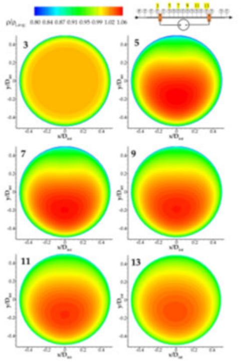
sCO$_2$ RESULTS

Effects of varying inlet temperature

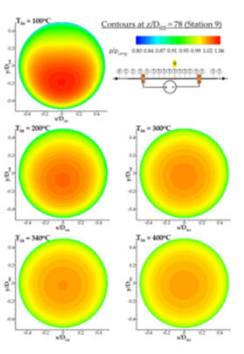




- Even at temperatures as high as 100°C, non-uniform variation in heat transfer cannot be neglected.
- With an increase in flow temperature, buoyancy effects on heat transfer decrease.
  - This can be seen from decreasing circumferential variation as well as Nusselt number distribution
- This is mainly due to the decrease in flow density itself.

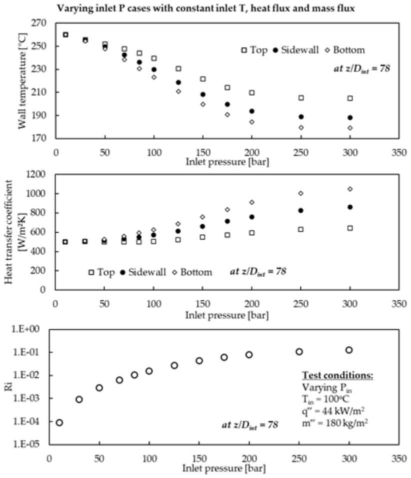


Density contours at different stations for case with P_{in} = 85bar, T_{in}=100°C

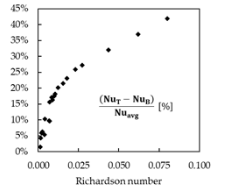


Density contours at Station 9 (z/D_{int} = 78) for different T_{in} cases

Effects of varying inlet pressure



- Higher circumferential variation in wall temperatures and heat transfer coefficients are observed at higher pressure
  - This is mainly due to the higher density of CO$_2$ at higher pressure, resulting in greater effects of buoyancy on heat transfer.
- Greater buoyancy effects at higher pressures are also reflected in Richardson number (Ri)
  - A strong correlation between Ri and maximum circumferential variation in Nusselt number has been observed showing clear diminishing effects of buoyancy with increasing Ri regardless of testing conditions



Nusselt number difference between top and bottom surface plotted against Richardson number for all the cases

CONCLUSIONS

- Strong effects of buoyancy on heat transfer are observed even at temperatures away from the pseudocritical temperature
  - Even at conditions such as 200 bar, 100°C
- The buoyancy effects decrease with temperature and increase with pressure
- Richardson number proves to be a good indicator to predict whether buoyancy will affect heat transfer or not.

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