The impact of measurement uncertainty on heat exchanger performance measurements in a sCO_2 test facility for power cycle applications

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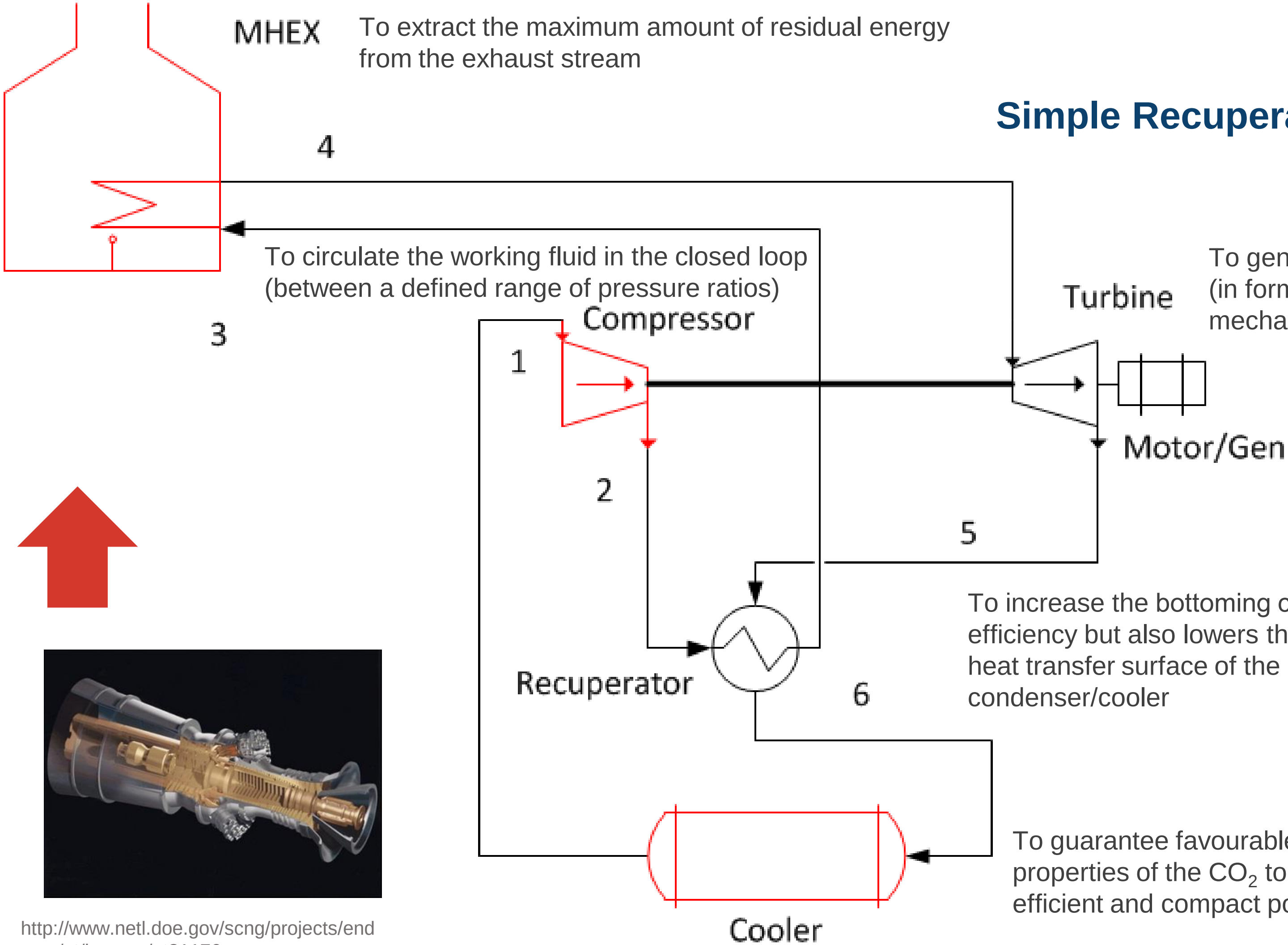
$S\text{-}CO_2$ Waste heat recovery system

Simple Recuperated Brayton



MHEX: To extract the maximum amount of residual energy from the exhaust stream

Compressor: To circulate the working fluid in the closed loop (between a defined range of pressure ratios)

Turbine: To generate additional power (in form of electricity or mechanical drive)

Recuperator: To increase the bottoming cycle's efficiency but also lowers the necessary heat transfer surface of the condenser/cooler

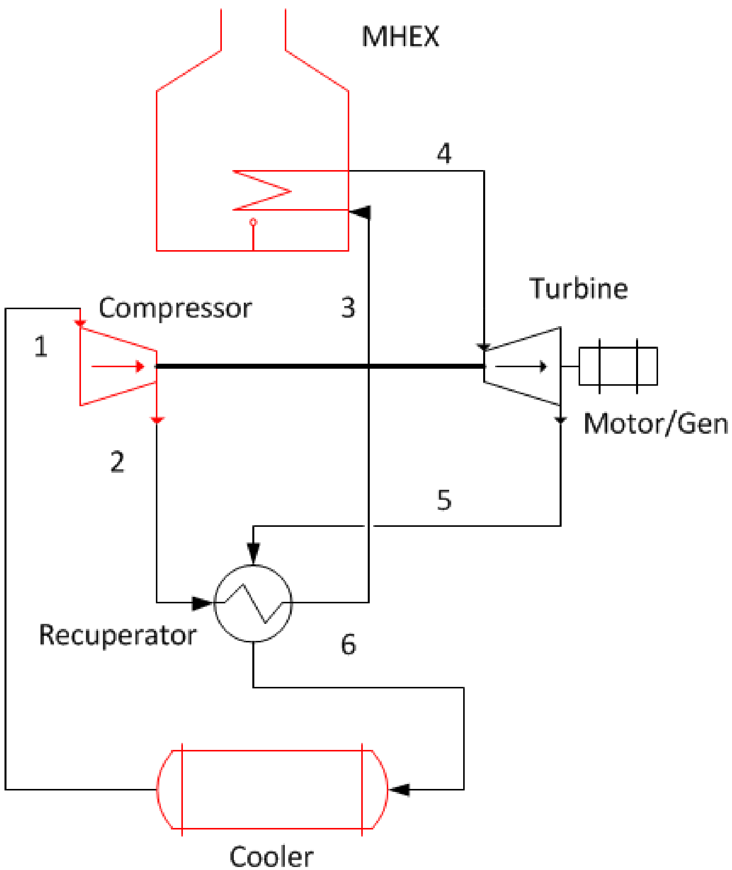
Cooler: To guarantee favourable critical properties of the CO_2 to deliver an efficient and compact power cycle

http://www.netl.doe.gov/scng/projects/end-use/at/images/at31176

Aim of the project

Design, build and commission a closed loop s-CO_2 system to enable critical component testing and whole cycle demonstration of a representative waste heat recovery system for marine GTs

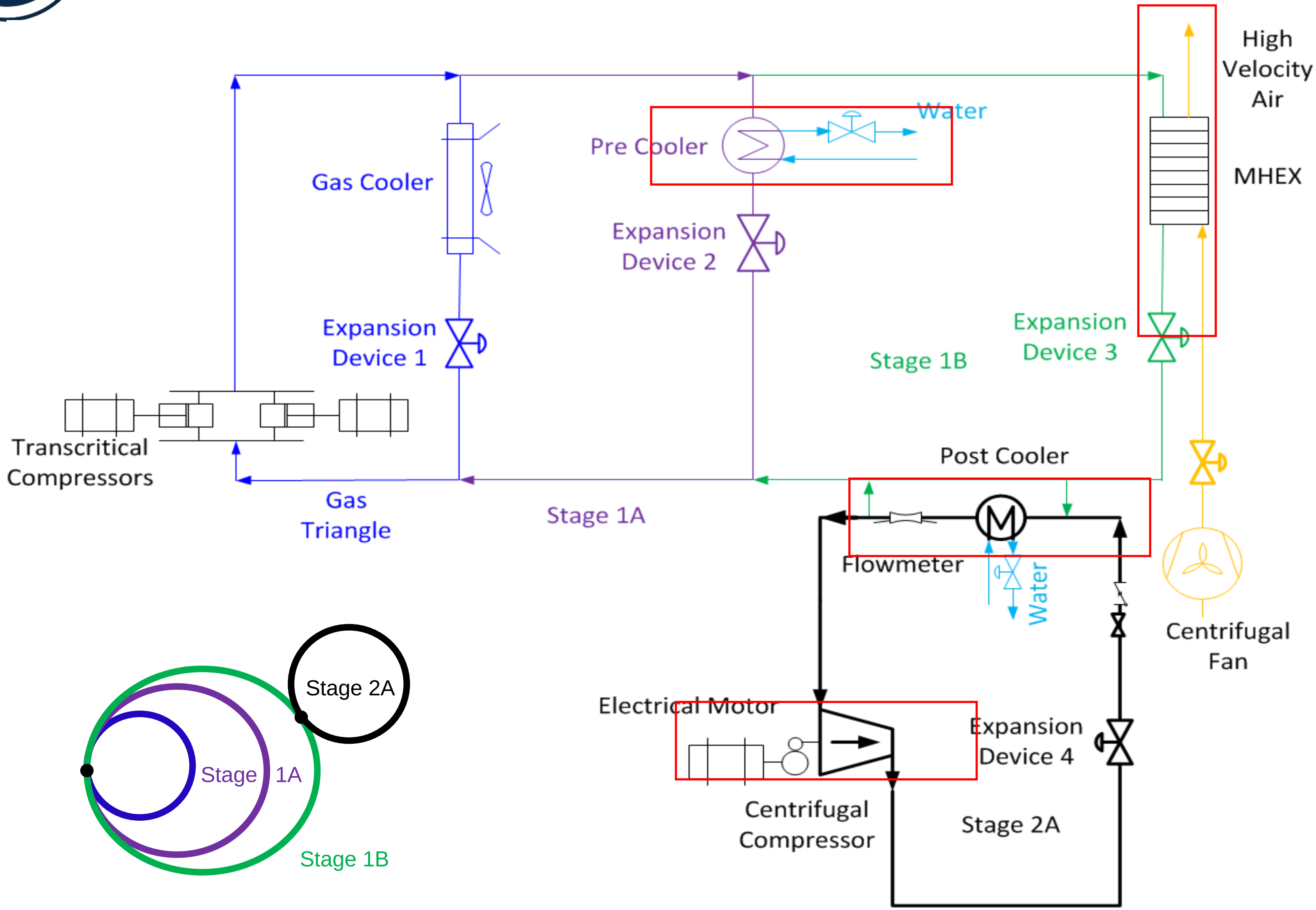
Objectives of the project



Scaled components to be tested in the rig

- Design s-CO_2 cycles for waste heat recovery (marine applications)
  - Select cycle for proof-of-the-concept
- Understand their design point, off-design and transient behaviour across a range of operating conditions
- Identify critical components and key requirements for rig testing
- Define full scope of rig testing
- Design & commission a s-CO_2 closed loop test facility

Test rig development - Roadmap

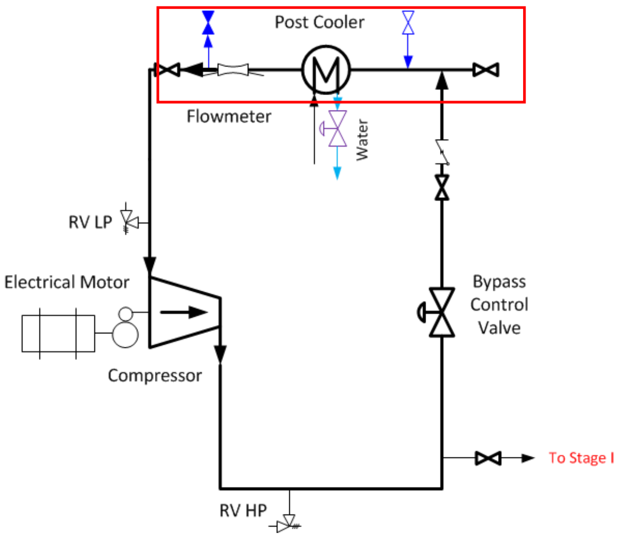


Uncertainty propagation

Post cooler: Printed Circuit Heat Exchanger operating near the critical conditions of the carbon dioxide (7.38 MPa and 304.25 K)

As part of the calibration and setting process (requirements for rig testing):

- Assess the potential measuring errors and their propagation
- Identify the instruments and methods of measurement required



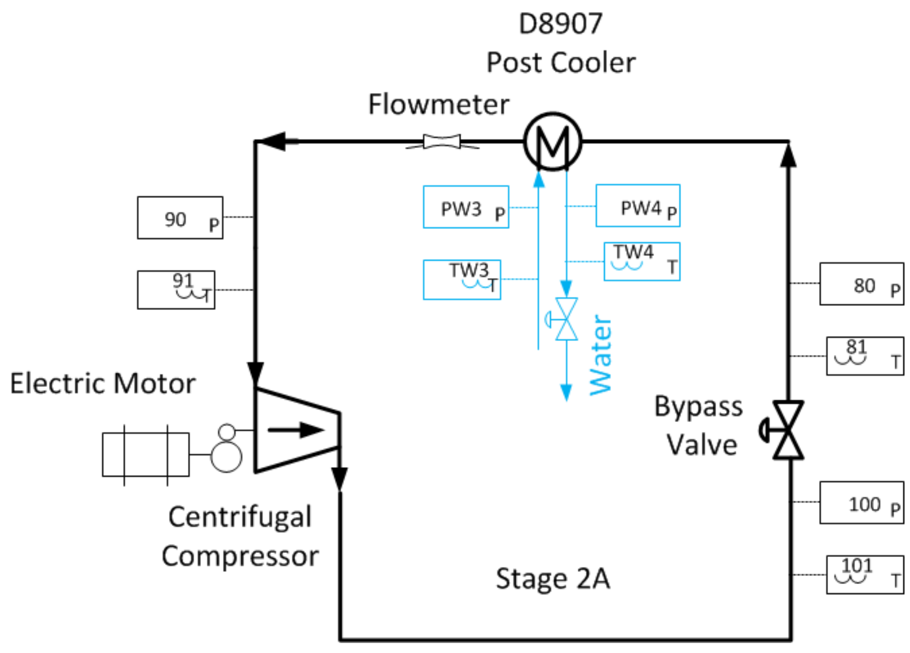
Stage 2

Objectives of the uncertainty analysis

- Verify the uncertainty required in each measurement station

- Assess of the instrumentation requirements
  - Pressure (gauge and differential)
  - Temperature
  - Mass flow

- Recognize possible error sources and assess over their minimization



Measurement Stations

Methods of measurement

- Performance test code proposed by the American Society of Mechanical Engineers (ASME) for single phase heat exchangers (ASME PTC 12.5)

- Performance parameters seek
  - Overall heat transfer coefficient (U)
  - Heat transfer rate (Q)
  - Nozzle-to-nozzle pressure drop (NPD)

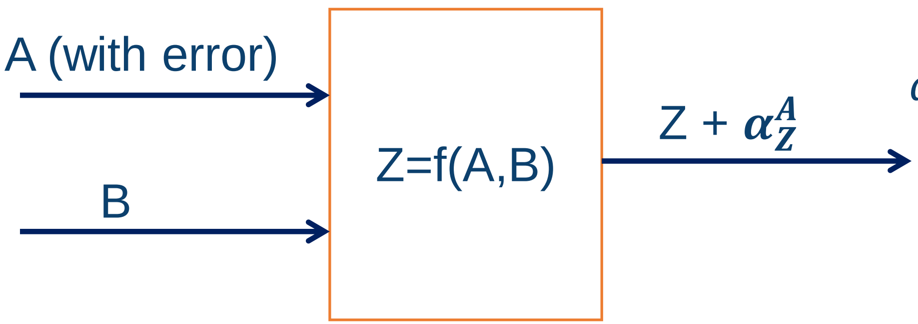
Instruments uncertainties under ASME PTC 12.5

Calibration	Less than
Temperature	± 0.1 °C
Pressure	± 0.3 %
Flow	± 2 - 3 %

Methodology

Functional Approach (for parametrical study)

$$Z = f(A,B)\ where\ the\ measured\ values \begin{cases} \bar{A} \pm \alpha_A \\ \bar{B} \pm \alpha_B \end{cases}$$



$$\alpha_Z^x = \boldsymbol{f}(\dots, \boldsymbol{x} + \alpha_x, \dots) - \boldsymbol{f}(\dots, \boldsymbol{x}, \dots)$$

$$(\boldsymbol{\alpha_Z})^2 = (\boldsymbol{\alpha_Z^A})^2 + (\boldsymbol{\alpha_Z^B})^2$$

Parametric studies to identify the main reasons of error propagation

Uncertainty propagation calculations implemented in MatLab

Methodology

Functional Approach (for parametrical study)

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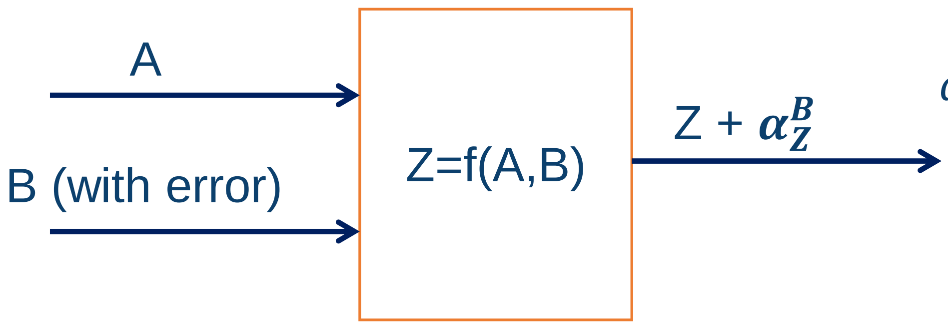

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Parametric studies to identify the main reasons of error propagation

Uncertainty propagation calculations implemented in MatLab

Methodology [2]

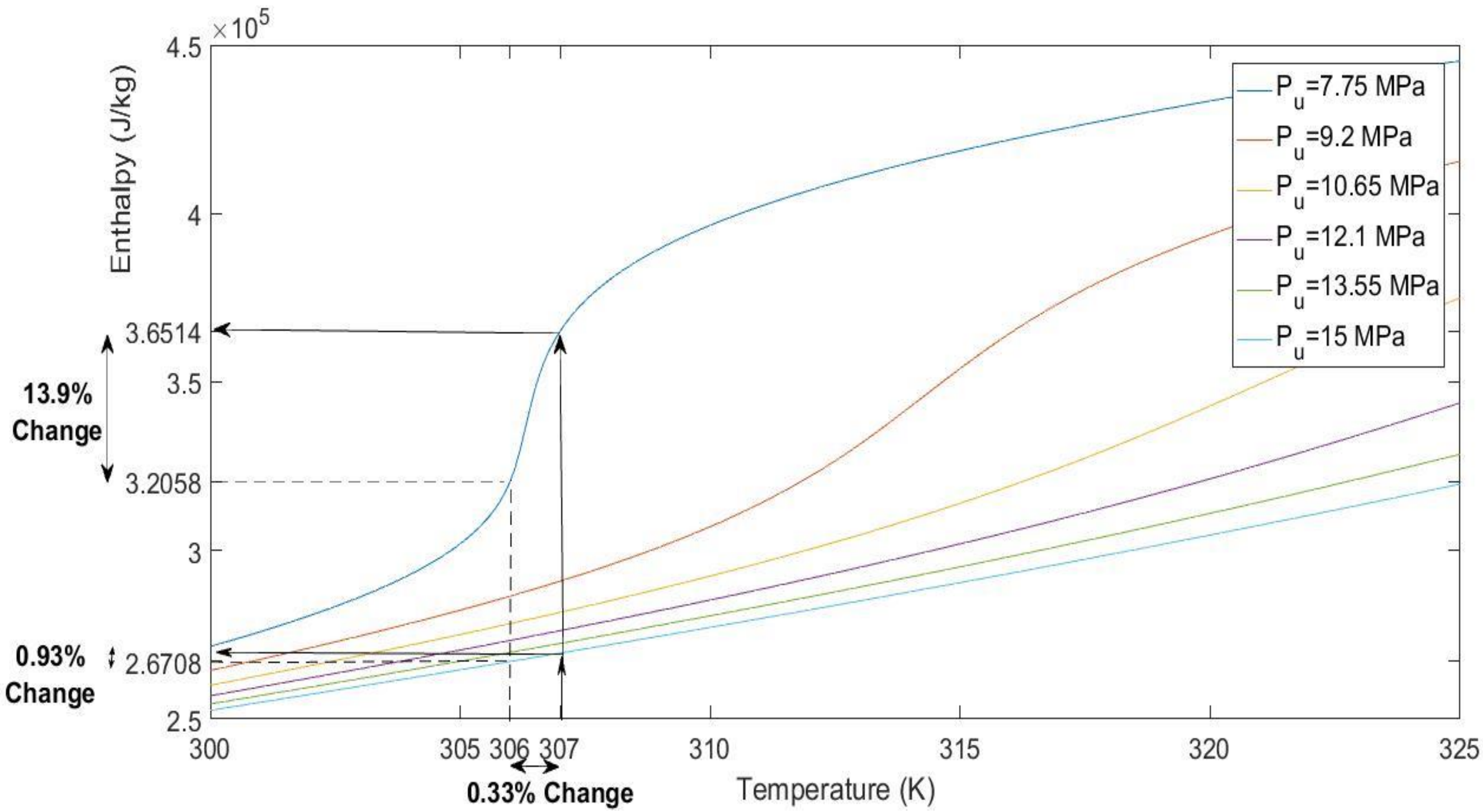
- **ASME PTC 12.5** define maximum allowable uncertainties for the following calculated performance parameters
  - Heat transfer rate, Q: limited to 10% **(exemplified here)**
  - Heat transfer coefficient, U: limited to 10%
  - Nozzle-to-nozzle Pressure Drop, NPD: limited to 12%

→ Based on this max. values, the requirements for the instrumentation can be estimated (i.e. fixing some parameters and testing parametrically others)

→ Identify which performance parameters are more sensible

Effect of using temperature in uncertainty estimation

Near C.P. - Higher changes in enthalpy and density with small errors in T and P

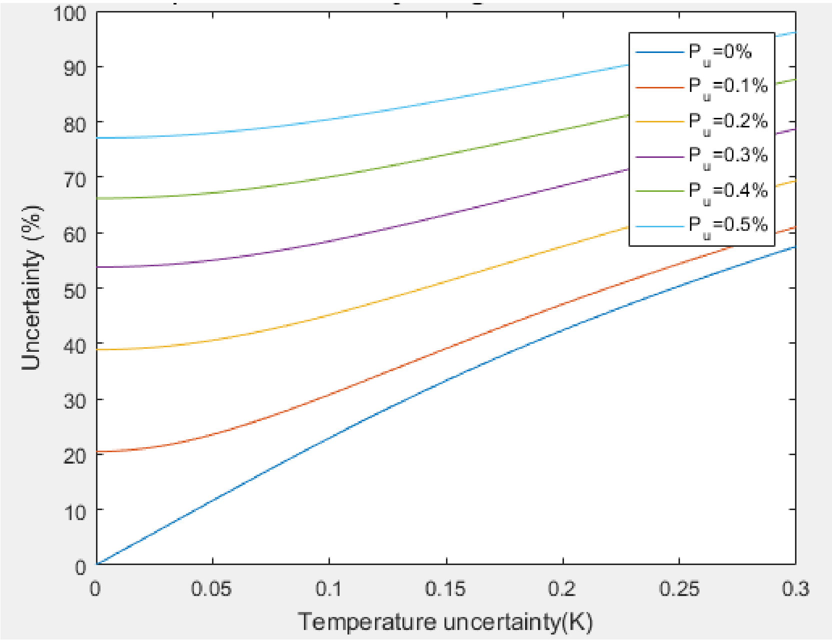


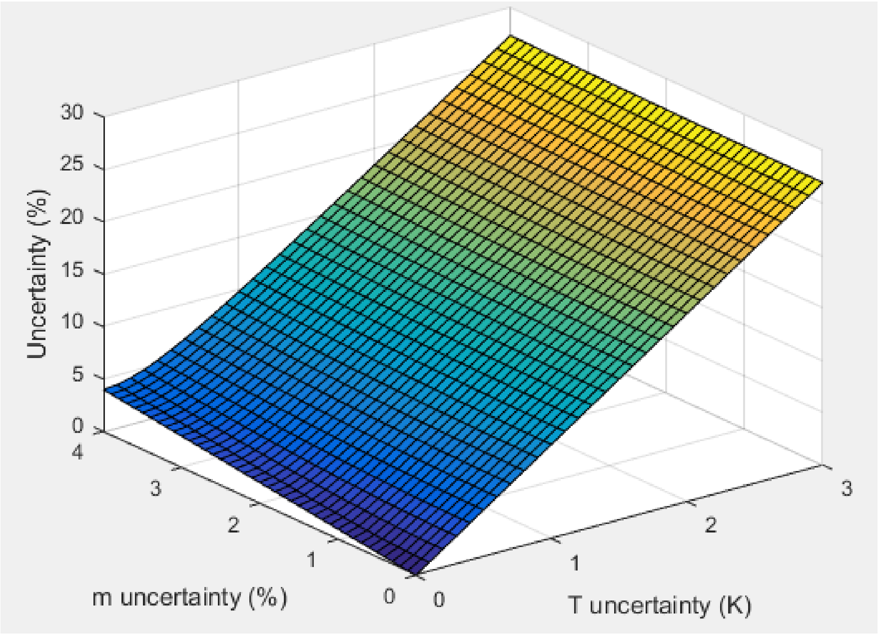
Variation of carbon dioxide enthalpy given a temperature variation of 1K near the critical temperature

Measurements uncertainty – Heat transfer rate [1]

Hot side (CO_2)

Cold side (H_2O)





Temperature uncertainty change effect on $Q_{hot\ side}$ uncertainty

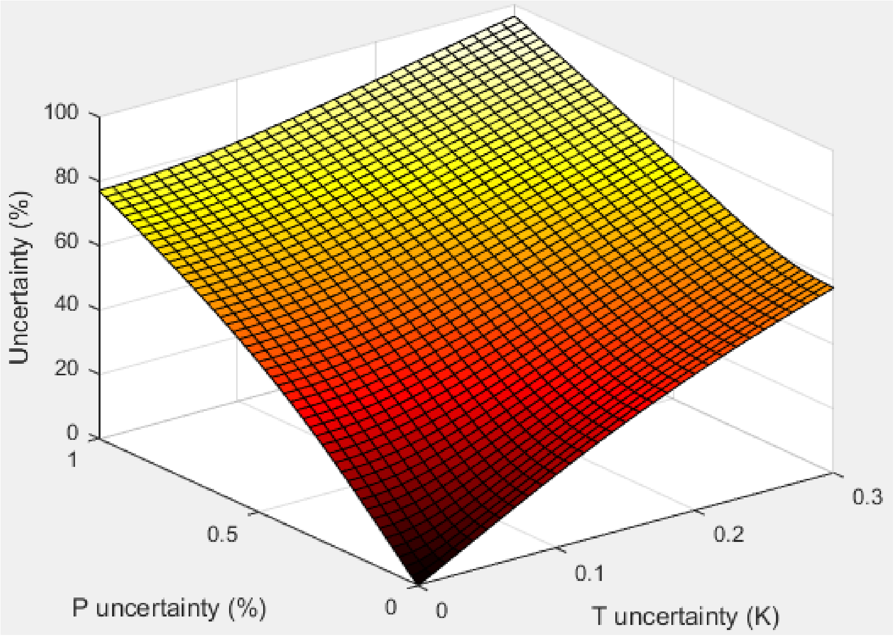
(with fixed mass flow uncertainty of 0.2%)

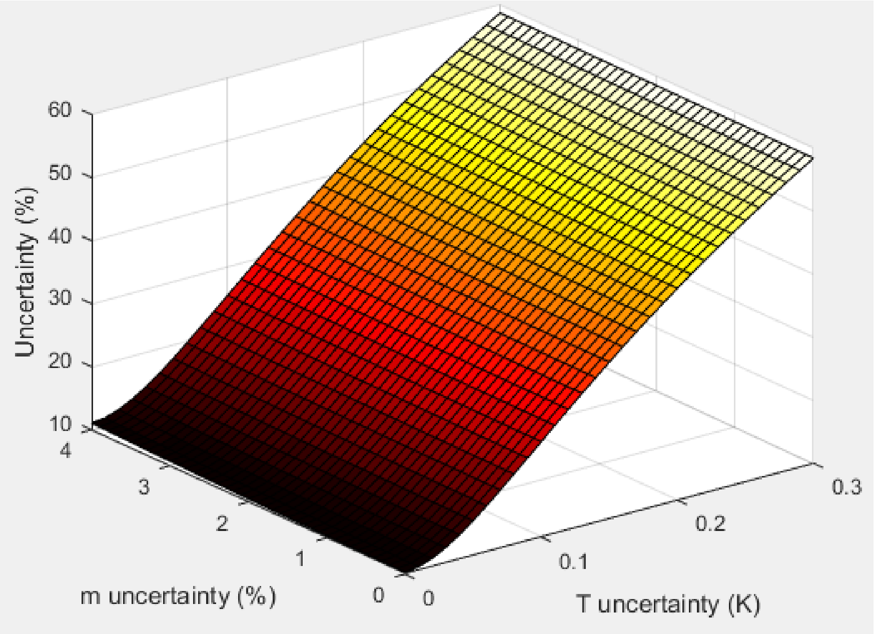
Uncertainty on $Q_{cold\ side}$ with fixed pressure uncertainty of 0.1%

Hot side imposes more demanding requirements for instrument selection

Measurements uncertainty – Heat transfer rate [2]

Hot side (CO_2)





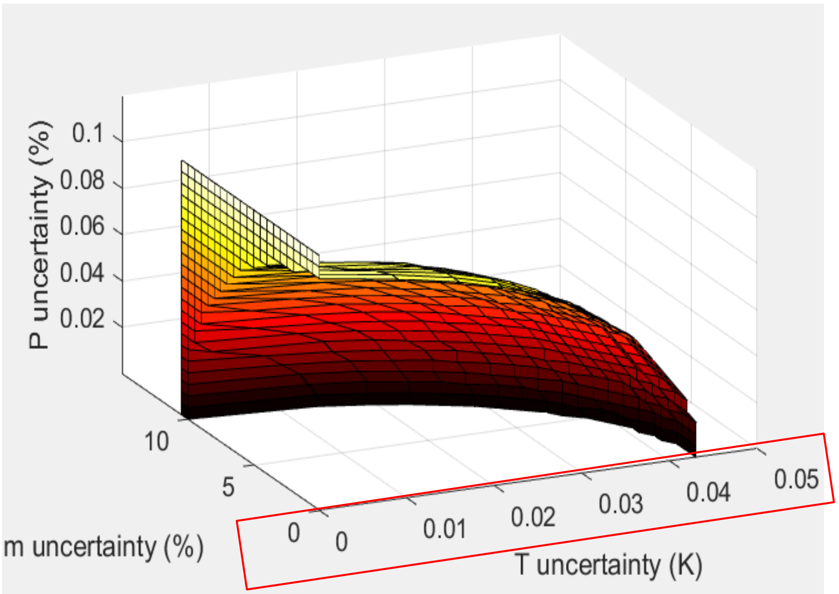
Uncertainty on $Q_{hot\ side}$ with fixed mass flow uncertainty of 0.2%

Uncertainty on $Q_{hot\ side}$ with fixed pressure uncertainty of 0.1%

Tighter uncertainties ranges are required for the measurement devices

Limits in the measurements uncertainty – f(T)

Hot side (CO_2)



Allowable calibration uncertainties of pressure, temperature and mass flow measuring systems in the post-cooler to achieved targets of ASME PTC 12.5

Uncertainties of Q, U and NPD calculated - CO_2 side

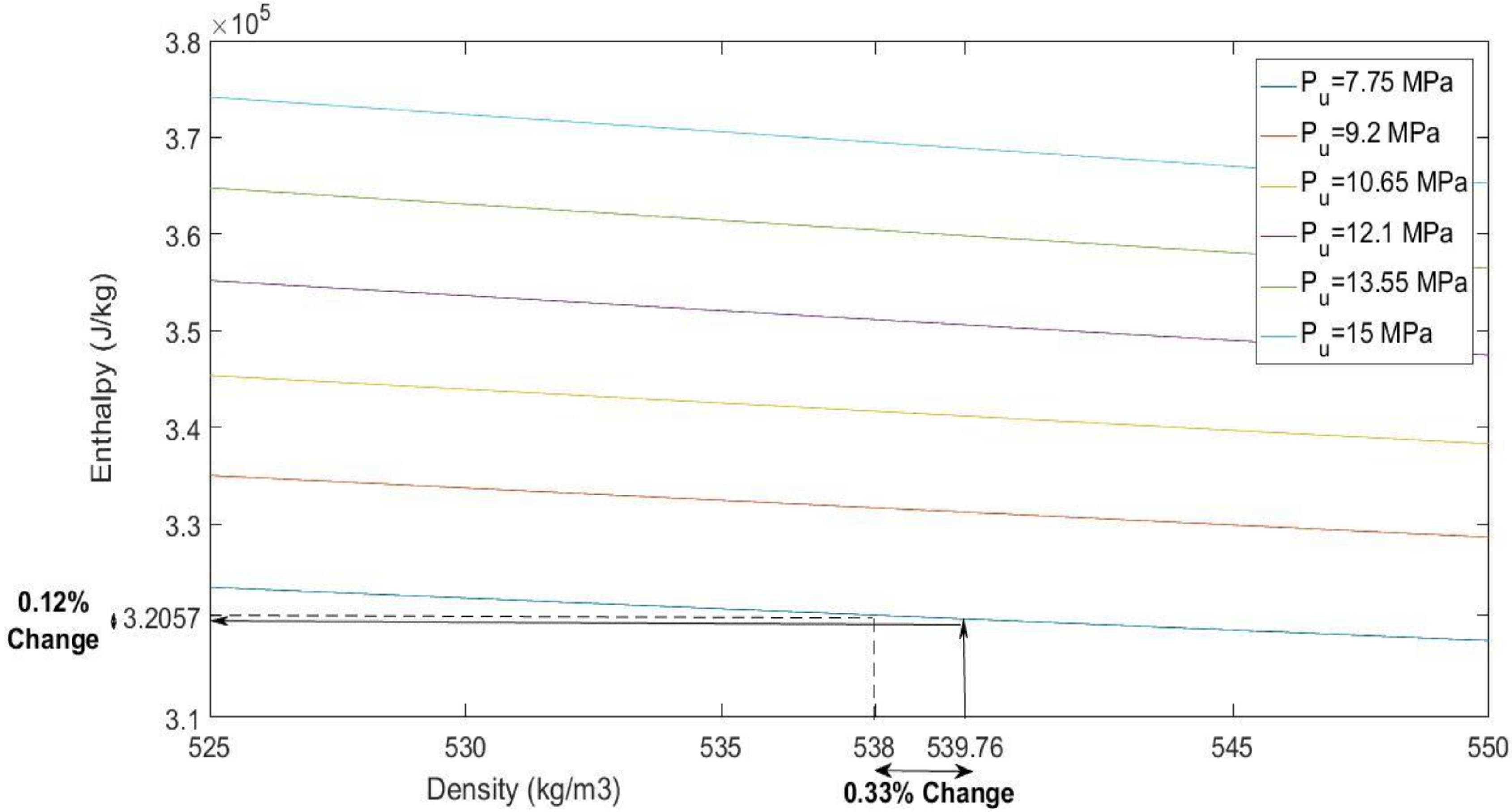
Assuming:

- All stations with the same instruments and same uncertainty
- Instrument selection T_u=0.15K, P_u=0.1% and m_u=0.2%

	Target	Calculated
Q uncertainty (%)	10	34.85
U uncertainty (%)	10	34.82
NPD uncertainty (%)	12	35.10

Is the temperature the best way to estimate enthalpy and density?

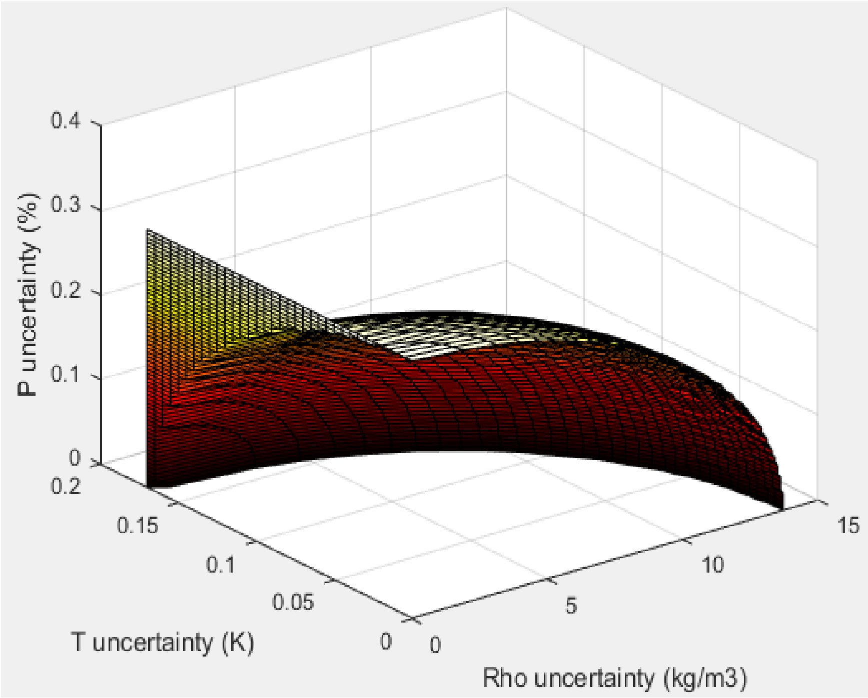
Effect of using density in uncertainty estimation



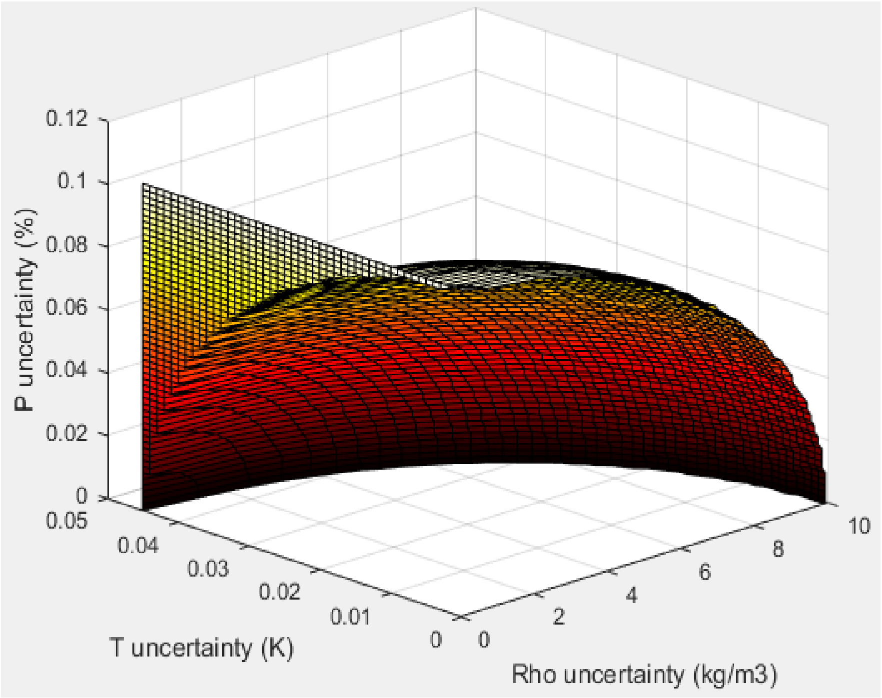
Variation of carbon dioxide enthalpy given a density variation of 1.76 kg/m^3 near the critical temperature

Limits in the measurements uncertainty – f(D)

Hot side (CO_2)



Density measured at the post cooler outlet



Density measured at the post cooler inlet

Allowable calibration uncertainties of pressure, temperature and density measuring systems in the post-cooler to achieved targets of ASME PTC 12.5 (fixed mass flow uncertainty of 0.2%)

Conclusions

- **Parametric study showed a great propagation of T uncertainties**
  - Careful measurements should be taken especially near the C.P.

- **Estimating CO_2 properties by using density and pressure is better than doing it by temperature and pressure**
  - Nearer to C.P. the properties change more abruptly with temperature, so the measuring of density is more beneficial at the post-cooler outlet

- **Uncertainty calculation methods:**
  - *Functional Approach*: suitable for a parametric study

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