R&D activities on sCO_2 in Europe: Components Challenge – Heat Exchangers [1]

Recuperators and coolers

Third episode – 6 March 2023

This webinar is in cooperation with 8 European R&D projects

ETN Global

COMPASsCO$_2$

SCARABEUS

CO$_2$OLHEAT

sCO$_2$-4-NPP

CARBOSOLA

sCO$_2$-Efekt

DESOLINATION

SOLAR sCO$_2$OL

Webinar content & speakers

- **Fundamentals, challenges and recent research** and development activity on sCO_2 cycle recuperators and coolers (Savvas Tassou – Brunel University of London

- **Printed circuit heat exchangers** for sCO_2 power cycles (Natalie Sarpong & Daniel Georges – Heatric)

- **Improvement of dry air cooler for the condensation of blended CO_2 using enhanced tubes** (Xavier Guerif – Kelvion Thermal Solutions)

sCO_2 Recuperators and coolers

Challenges and recent research and development

Savvas Tassou and Lei Chai

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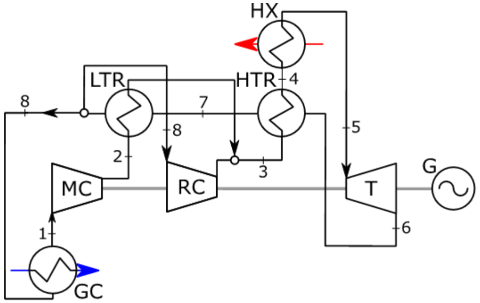
Brunel University London
Research and Development on sCO_2 cycles and components

Institute of Energy Futures

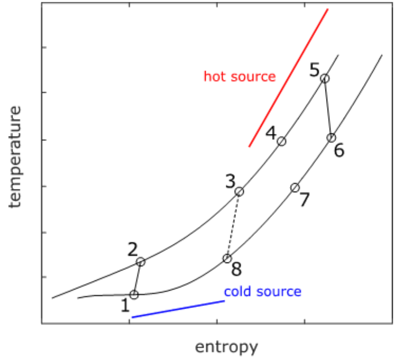
- CO2 refrigeration ; CO2 high temperature heat pumps ; sCO2 heat to power
- I-ThERM - (60 kWe simple recuperative cycle)
- CO2OLHEAT – (2.0 MWe waste heat to power)
- SCOTWOHR – UKRI – Cycle optimisation for heat recovery and HXs

Heat exchangers in sCO_2 cycles

- Many sCO2 cycle configurations possible for different applications
- Number of heat exchangers can vary
- Minimum 3 (heater, gas cooler and recuperator) in simple recuperated cycle.
- Multiple heat exchangers in complex cycles
- Heat exchangers responsible for significant capital cost in sCO2 systems



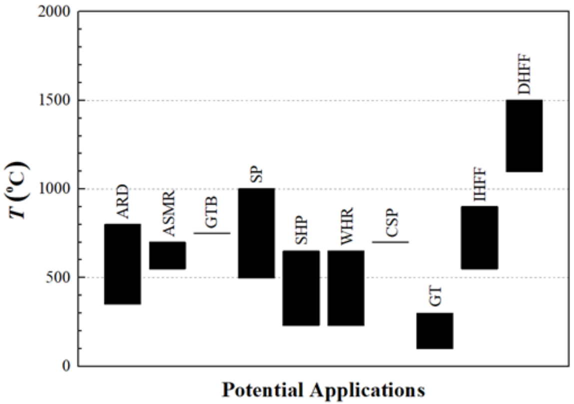
Recompression cycle

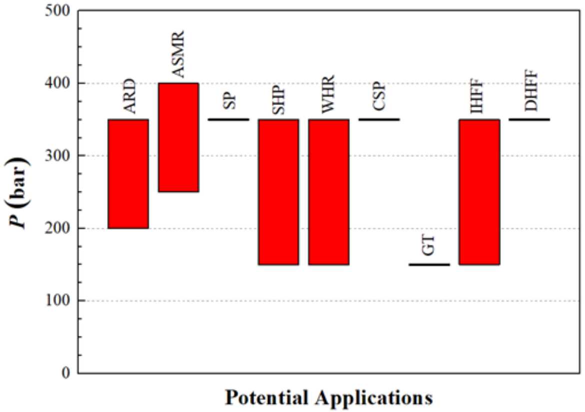


sCO$_2$ heat exchanger design considerations

Very favourable thermophysical properties of CO2 in supercritical region can enable wide range of applications and operating conditions.

- Operation at high pressures and temperatures can lead to high cycle efficiencies.
- Implications on:
  - material selection
  - manufacturing methods
  - life cycle costs



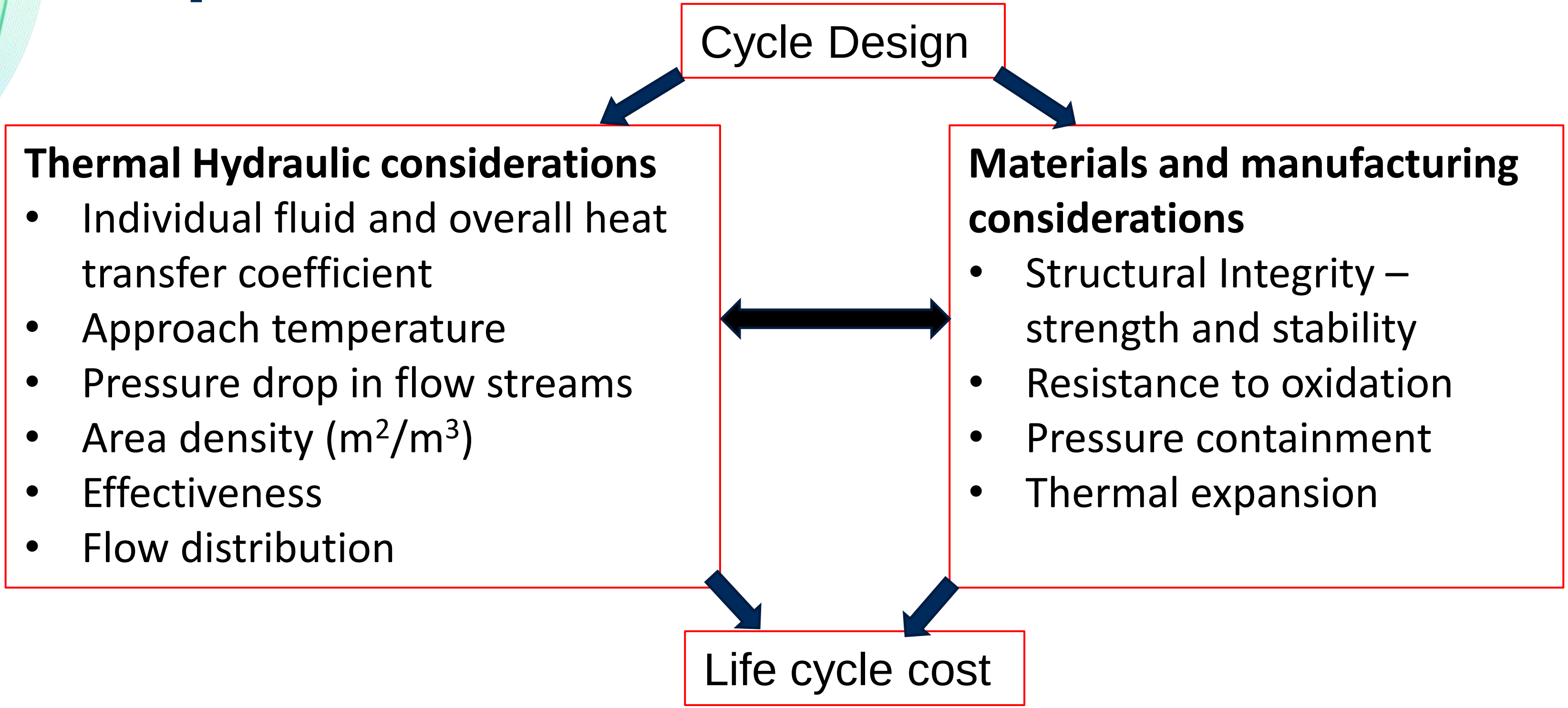


ARD (advanced reactor designs)
ASMR (advanced small modular reactors),
GTB (gas turbine bottoming),
SP (shipboard propulsion),
SHP (shipboard house power),

WHR (waste heat recovery),
CSP (concentrated solar power),
GT (geothermal),
IHFF (indirect heating fossil fuel),
DHFF (direct heating fossil fuel).

From: Mendez and Rochau, SAND-2018-6187, Sandia National Laboratories, Albuquerque, New Mexico, 2018.

Challenges for heat exchanges/ recuperators and coolers



Cycle Design

Thermal Hydraulic considerations

- Individual fluid and overall heat transfer coefficient
- Approach temperature
- Pressure drop in flow streams
- Area density (m^2/m^3)
- Effectiveness
- Flow distribution

Materials and manufacturing considerations

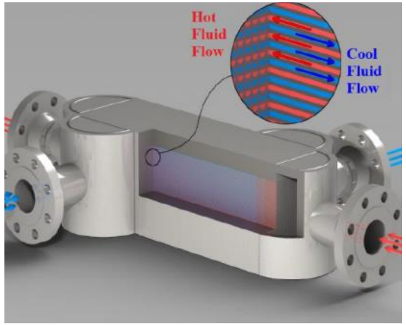
- Structural Integrity – strength and stability
- Resistance to oxidation
- Pressure containment
- Thermal expansion

Life cycle cost

Heat exchanger types for recuperators

Recuperators (sCO2 to sCO2)

- Shell and tube
- Plate and shell
- Spiral wound exchanger
- Compact heat exchangers
  - Printed Circuit (PCHE)
  - Microtube heat exchangers
  - Plate matrix heat exchangers
  - Pin finned heat exchangers
  - Additively Manufactured HXs



PCHE

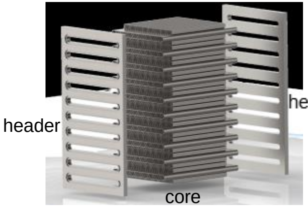
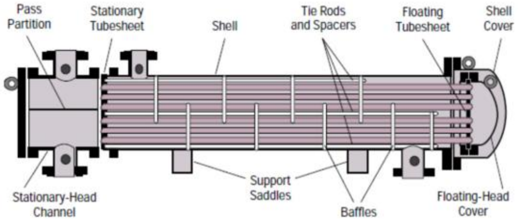


Plate-matrix HX

Musgrove et.al. 2018
CO2 Power Cycles Symposium

Shell and tube

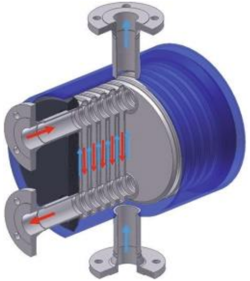


(https://www.enggcyclopedia.com/2019)

Spirally wound

http://www.wingtech.com/en

Plate and shell



www.elevatedflaresystem.com/

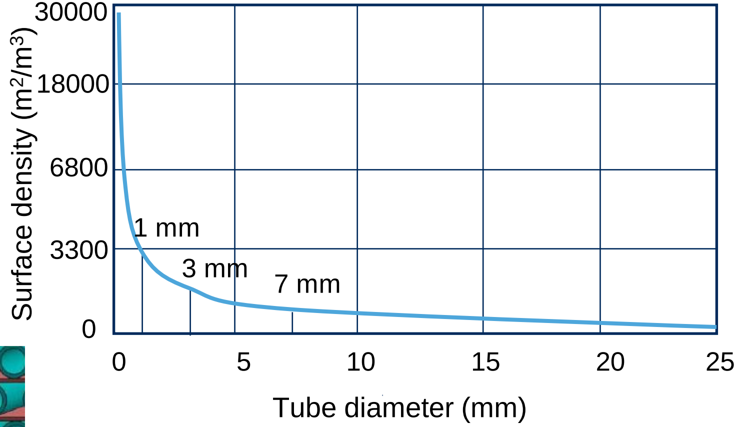
Microtube heat exchangers

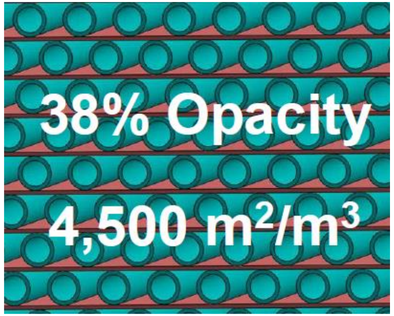
Can be used as primary heaters, recuperators and coolers

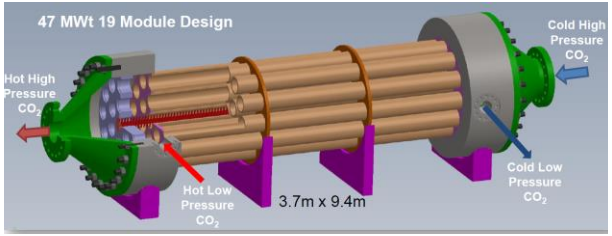
- Recuperators very similar to shell and tube
- Numerous tubes in bundles in a shell

Category	Units	#
Duty @ 20 kg/min sCO_2	kW	150
Effectiveness	%	97.5
High Pressure Outlet T	°C	529
High Pressure Delta P	bar	< 0.1
Low Pressure Outlet T	°C	189
Low Pressure Delta P	bar	0.1
Length	m (ft)	2.78 (9.12)
Pipe Dia	m (ft)	0.23 (0.75)
Flange Dia	m (ft)	0.38 (1.25)

Prototype design of microtube HX for STEP project







Thar Energy, 2018 DE-FE0026273 project

Microtube heat exchangers – thermal-hydraulic modelling for optimisation

$$U_i A_i = \frac{1}{\frac{1}{h_{c,i} A_{c,i}} + R_{s,i} + \frac{1}{h_{h,i} A_{h,i}}}$$

$$\varepsilon_i = \frac{1 - \exp[-NTU_i(1 - C_i^*)]}{1 - C_i^* \exp[-NTU_i(1 - C_i^*)]}$$

$$NTU_i = \frac{U_i A_i}{C_{\min,i}}$$

$$C_i^* = \frac{C_{\min,i}}{C_{\max,i}}$$

$$C_{\min,i} = \min(\dot{m}_{c,i}\, c_{pc,i},\ \dot{m}_{h,i}\, c_{ph,i})$$

$$C_{\max,i} = \max(\dot{m}_{c,i}\, c_{pc,i},\ \dot{m}_{h,i}\, c_{ph,i})$$

Gnielinski correlations

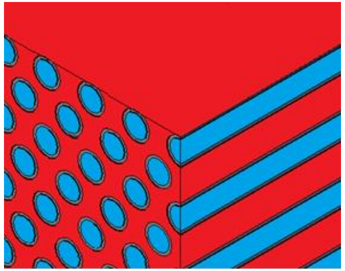
$$Nu_{c,i} = \frac{(f_{c,i}/8)(Re_{c,i} - 1000)Pr_{c,i}}{1 + 12.7(f_{c,i}/8)^{1/2}(Pr_{c,i}^{2/3} - 1)}$$

Cold side

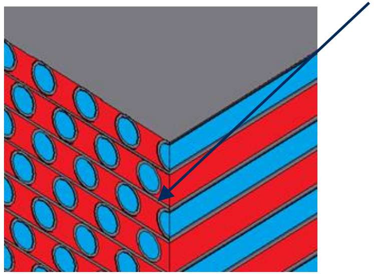
$$Nu_{h,i} = \frac{(f_{h,i}/8)(Re_{h,i} - 1000)Pr_{h,i}}{1 + 12.7(f_{h,i}/8)^{1/2}(Pr_{h,i}^{2/3} - 1)}$$

Hot side

Modelling of compact heat exchangers for CO2 ideally should apply the segmental approach due to large changes in fluid properties particularly close to the critical point.

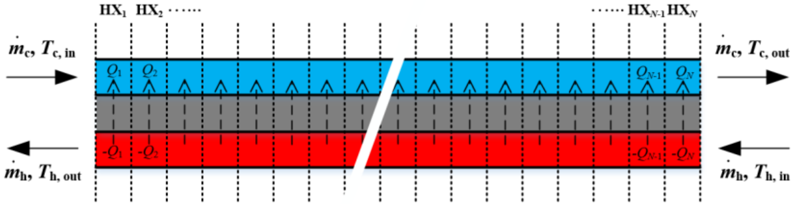


MTHE



Separator sheets

MTHE-SS (separator sheets)



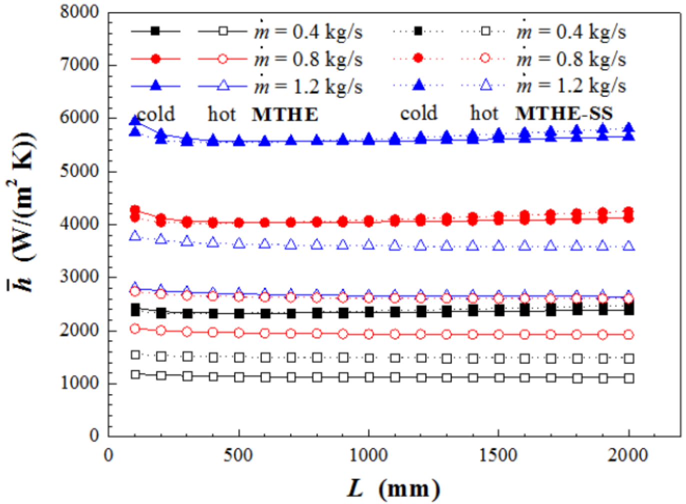
Microtube heat exchangers
Comparison between tube bundles with and without separator sheets

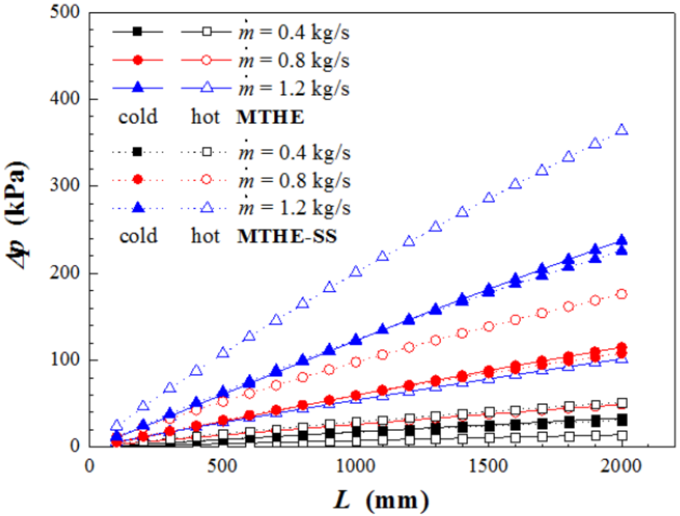
Microtube with baffles – cross counter flow

Tube diameter 1.0 mm; thickness 0.1 mm

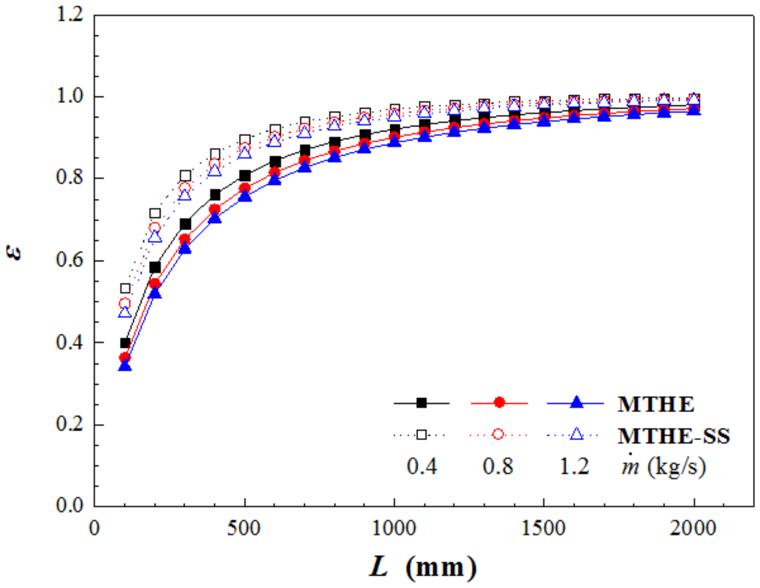
Microtube with separator sheets counter current flow

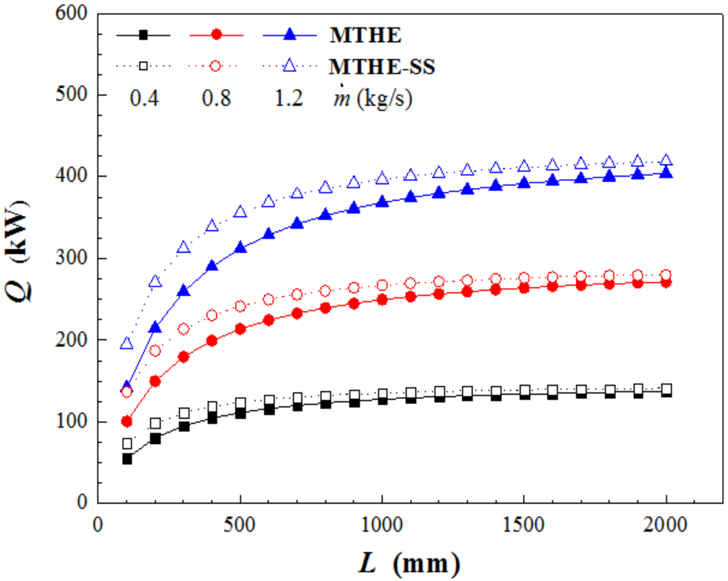
$T_{c,\,in}$ = 100 °C, $T_{h,\,in}$ = 400 °C, $p_{c,\,in}$ = 150 bar, $p_{h,\,in}$ = 75 bar,





Microtube heat exchangers





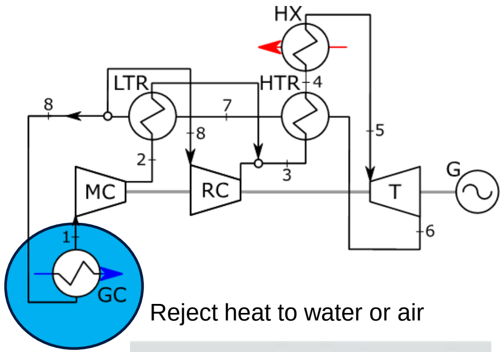
Coolers

- Less demanding operating conditions than recuperators – (max. ambient temperature; pressure equalisation in power block; CO2 management).
  sCO2 inlet 80-100 bar; 80-100 ºC; CO2 outlet 32-40 ºC.

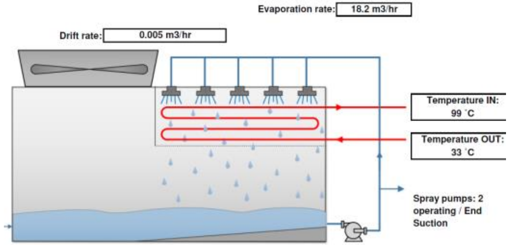
- Heat Exchangers
  - Rejection of heat to water
    - Shell and tube
    - Plate and shell
    - Compact heat exchangers

      (important to be able to clean and repair tubes and flow passages-or filter/treat the water)

  - Rejection to air (CO2 to air – direct cooling)
    - Finned tube heat exchangers (dry coolers)
    - Bare tube heat exchangers (wet coolers)
    - Adiabatic coolers
    - Microtube heat exchangers



Reject heat to water or air

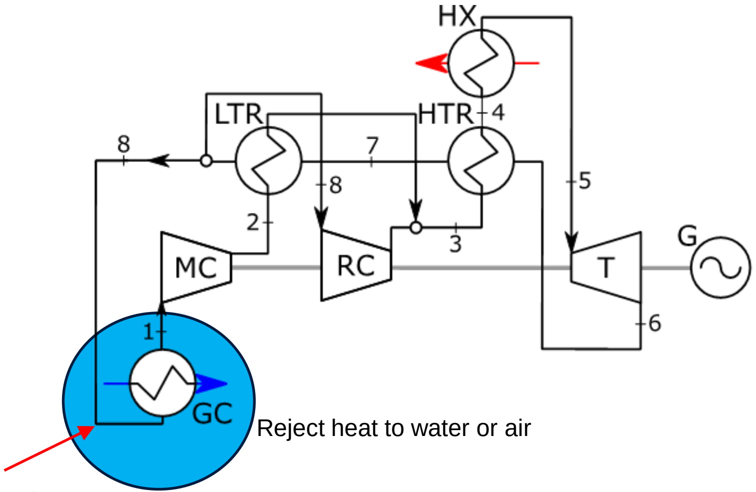


Wet cooler (Courtesy Alfa Laval)

Coolers

Design and control considerations

- Effective heat transfer to reduce footprint and cost – low approach temperature
- Low pressure drop
- Fast response to sudden changes in load – emergency shutdown of power plant.
- Control strategies to ensure design compressor inlet temperature is maintained during changes in load, ambient temperatures etc.



Reject heat to water or air

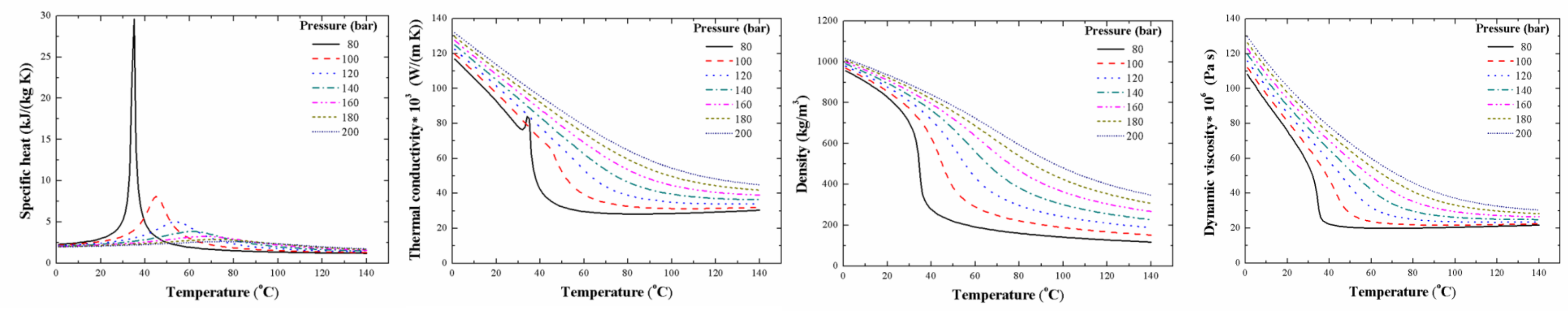
Summary

- PCHEs well established as recuperators
- Other emerging compact designs – it will take time before they are established commercially for multi-MWth applications.
- Selection of cooler type will depend on availability of water and ambient temperature.
- Heat transfer and pressure drop correlations based on modelling and testing on single tubes or small components-need to be validated on larger full size components
- Wet direct cooling may be a good lower life cycle cost option compared to indirect cooling – area of further research?

Back up slides

CO2 working fluid in sCO2 power cycles

- CO2 is a dense working fluid with very good thermophysical properties
- Very compact heat transfer equipment compared to other heat transfer fluids used in power generation
- Low critical temperature, 31.1 ^{o}C; Critical pressure 73.8 bar
- Very good thermophysical properties particularly close to critical point

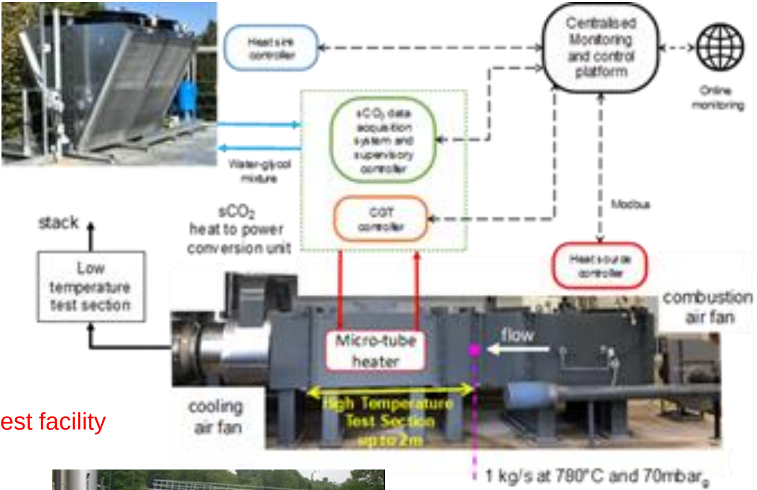


Thermophysical properties of CO_2 at different pressures versus temperature (constructed using Refprop)

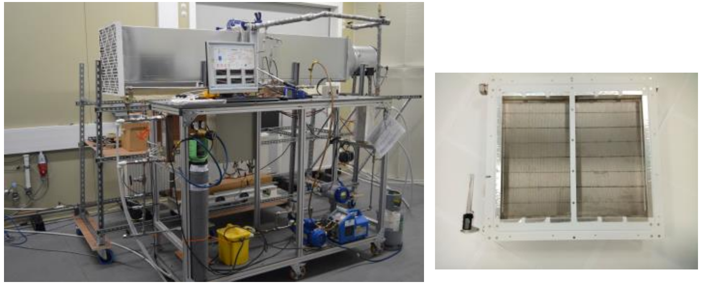
Chai&Tassou Journal of Enhanced Heat Transfer 29(4):1–40 (2022)

Research and Development on sCO2 cycles and components

60 kWe sCO2 power block



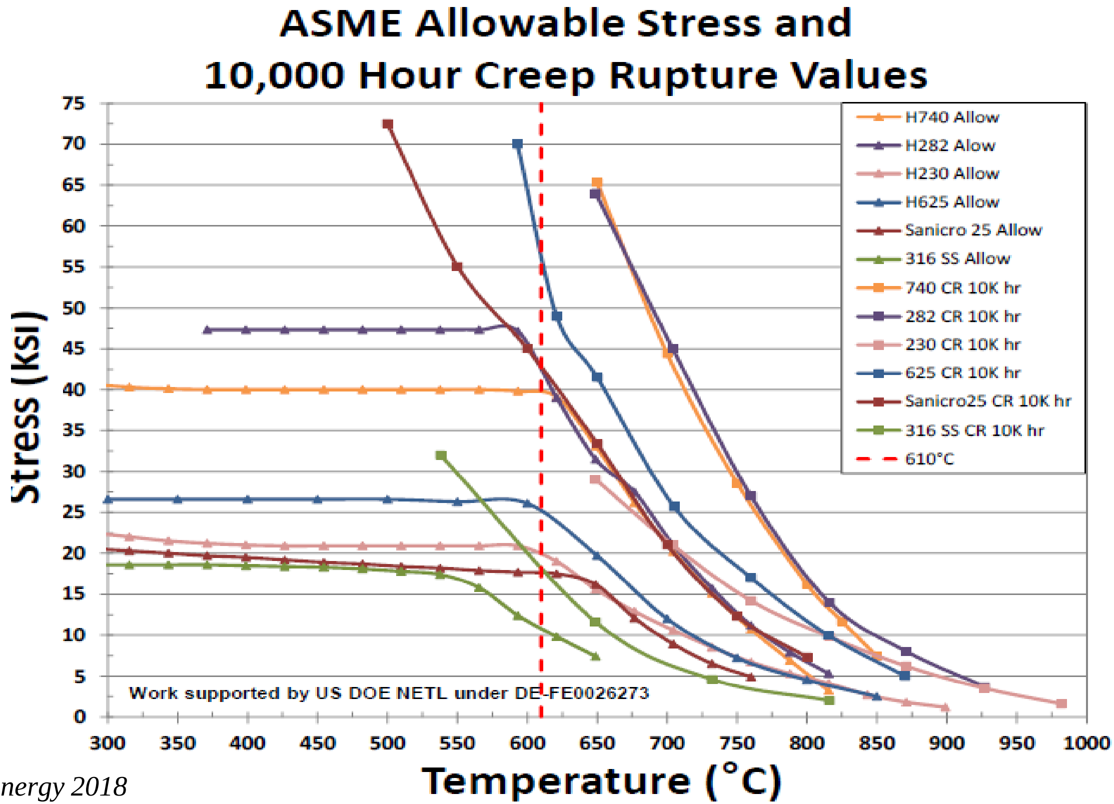
sCO2 test facility



Microtube test facility

Gas cooler test facility

CO2 working fluid in sCO2 power cycles



Courtesy – Thar Energy 2018

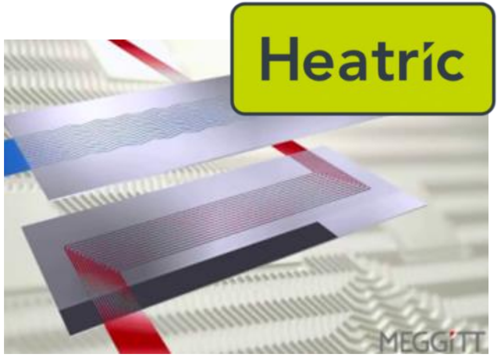
Printed circuit heat exchangers for sCO_2 power cycles

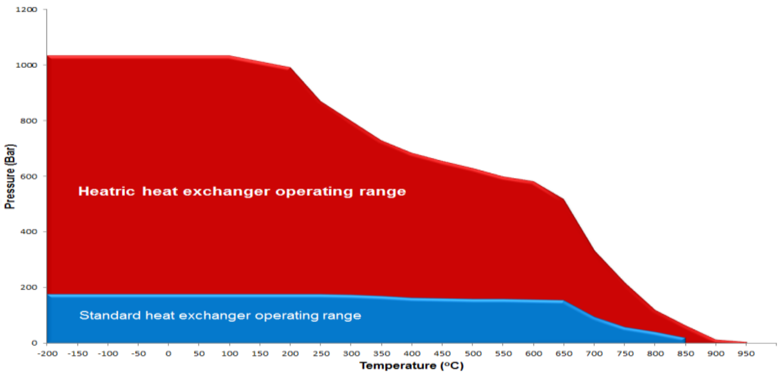
presented by Daniel Georges and Natalie Sarpong

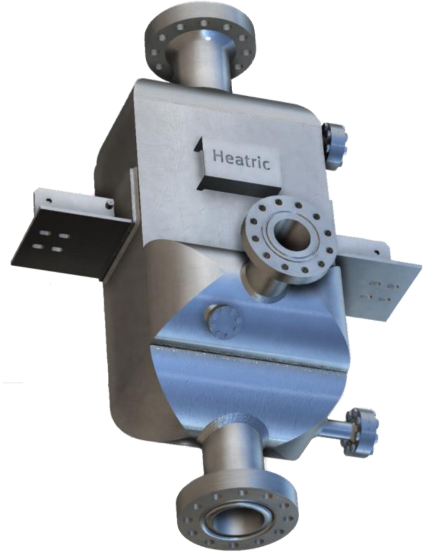
What is a PCHE?

Printed Circuit Heat Exchanger

- Chemically etched plates
- Diffusion bonded core
- High temperature and pressure capability







PCHE uses in sCO_2 cycles

Recuperators and Coolers

- Recuperators
    - Recover heat from the hot side of the cycle to heat the cold side
    - Improves efficiency

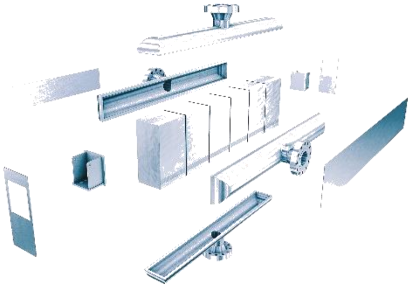
- Coolers
    - Cools the cycle prior to re-entering the compressor
    - For closed loop cooling systems

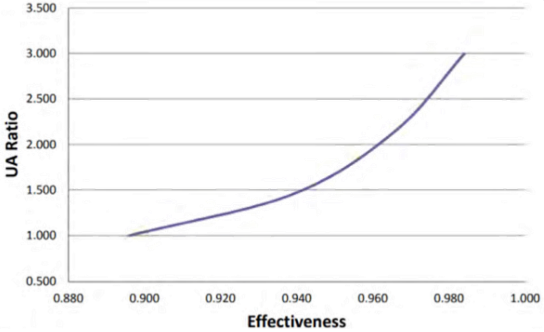
- Advantages
    - Performance
    - Safety
    - Size
    - Cost

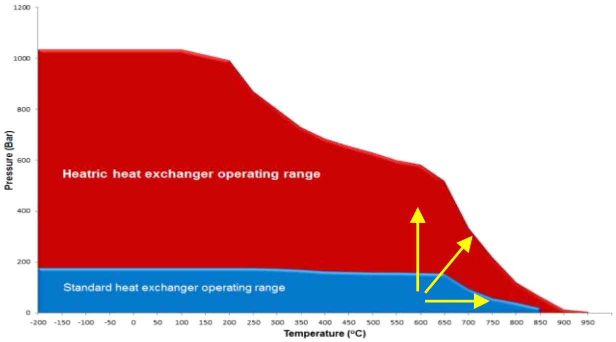
Challenges

Design Conditions

- Higher T/P Operation
- Larger Temperature Span
- Material selection based on DTmax





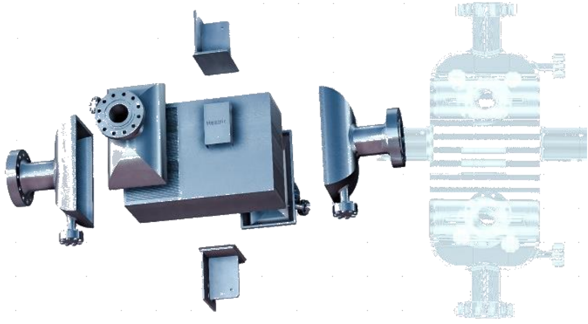


STEP High Temperature recuperator

Challenges

Materials

- Exotic materials
- Non-standard components
- Procurement Lead Times

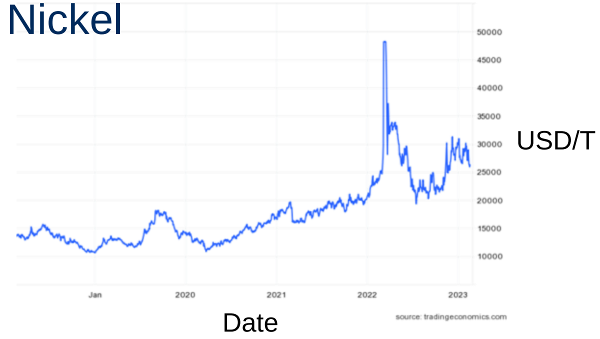


Grade	Ni (wt%)	Co (wt%)	Mo (wt%)
316L	11	0	2
617	52	9	12

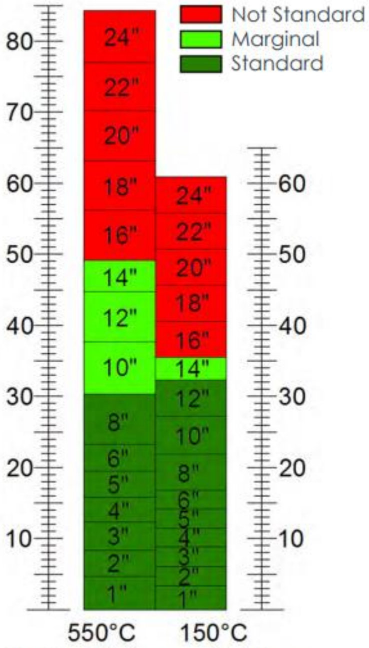
Iron Ore

source: tradingeconomics.com

Nickel



source: tradingeconomics.com

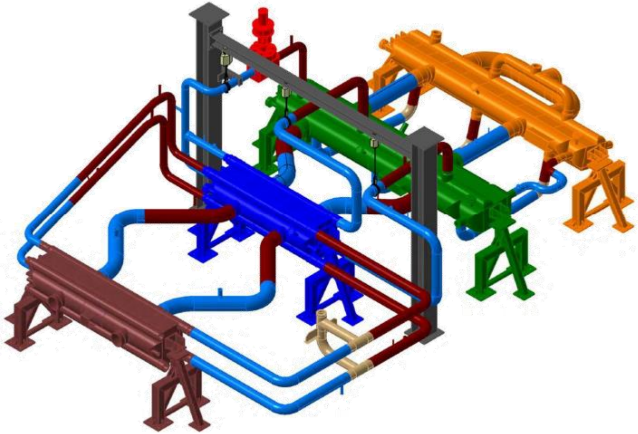


316 Pipe thickness vs. Std Pipe schedule (250 Bar pressure)

Challenges

Complexity

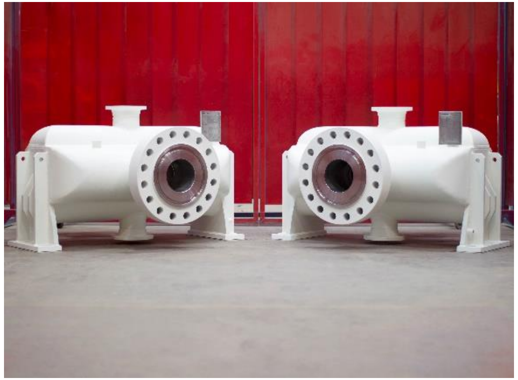
- Novel
- Engineering Development
- Reduced Agility



Solutions

Modularisation

- Smaller components
- Reduced Lead Times
- Efficient Engineering Design
- Improved Control
- Reduced Downtime



Path to Commercialisation

MAN

MAN Energy Solutions
Future in the making

STEP DEMO

$CO_2OLHEAT$

R&D activities on sCO_2 in Europe:

Recuperators and coolers

Improvement of dry air cooler for condensation of blended CO_2 using enhanced tubes

Summary

- Kelvion Thermal Solutions
- What is an Air Fin Cooler (AFC) ?
- Enhanced finned tubes
- Test tube section
- Prototype
- Full scale savings

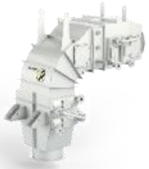
Kelvion Thermal Solutions

- Experts in heat exchange – Since 1920
- 1500 employees all over the world
- Five manufacturing sites based in US, China, France, Poland and Netherlands
- Large portfolio:


Air Cooled Condenser


Air Fin Cooler


Air Dryer


Economizer


Cooling Tower


Shell & Tube


Desublimators

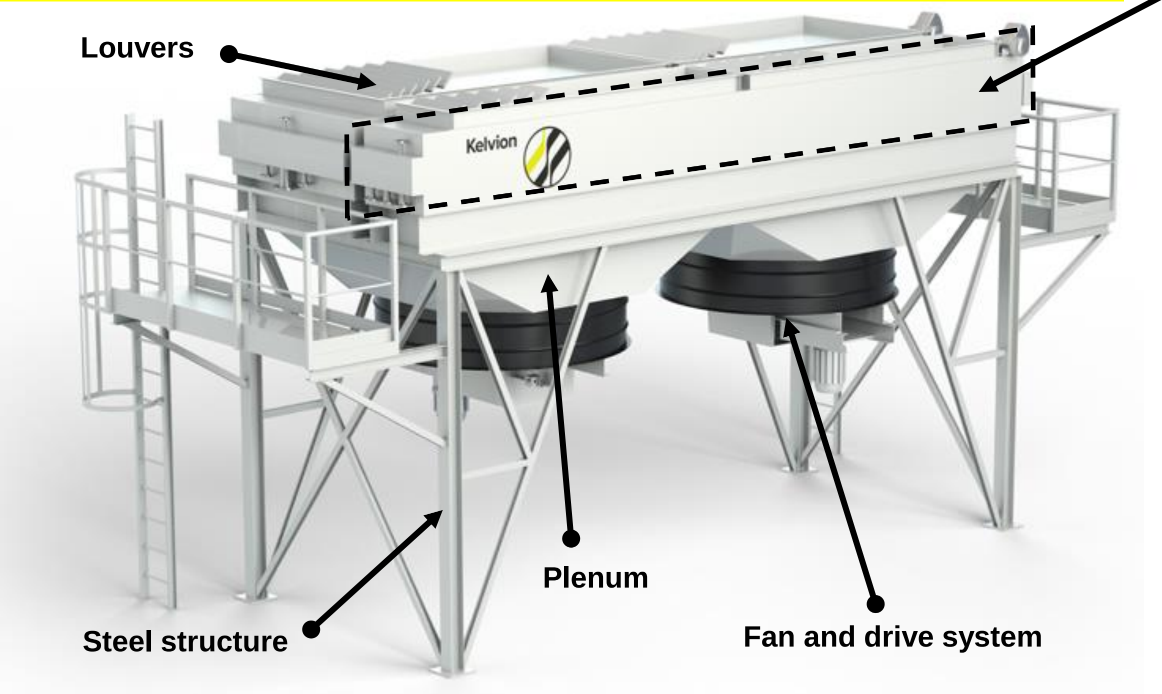

Printed Circuit Heat Exchanger – K°Bond


Rekuluvo / Rekugavo


K°Flex

What is an Air Fin Cooler (AFC) ?

AFC ALU Forced draft (fan below bundle)



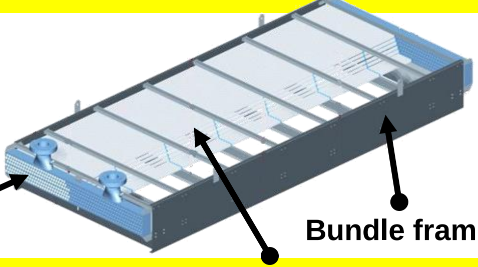
Louvers

Steel structure

Plenum

Fan and drive system

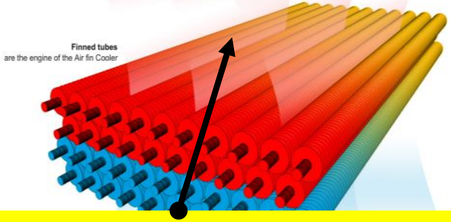
TYPICAL PROCESS BUNDLE



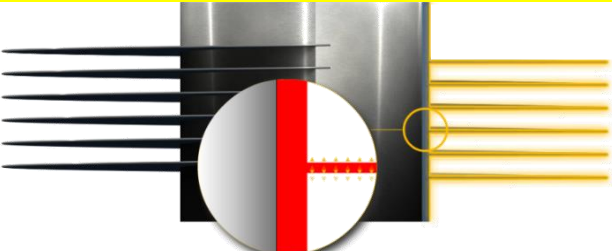
Headers

Bundle frame

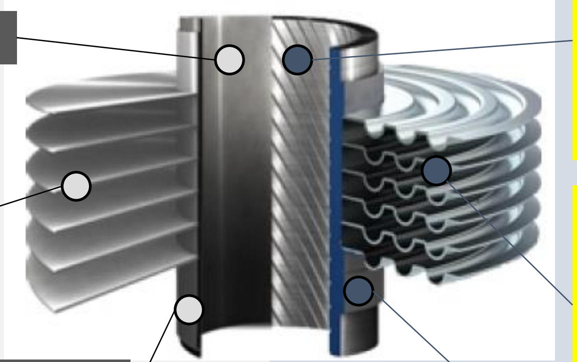
FINNED TUBES



TYPICAL FINNED TUBE



Enhanced finned tube



Standard Extruded Finned Tube

Plain internal tube

Smooth extruded fins

Aluminum sleeve protection

DIESTA

Enhanced internal tube surface using helicoidal structure which increase turbulences:

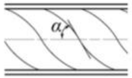
- Increase thermal heat transfer coefficient **Hi**
- Increase pressure drop **ΔPi**

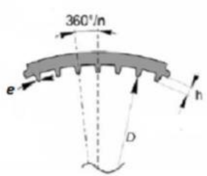
Enhanced external fin surface using grooves which increase turbulences & improves air distribution:

- Increase thermal heat transfer coefficient **Ha**
- Increase pressure drop **ΔPa**

Aluminum sleeve protection

Helicoidal inner fins : challenge



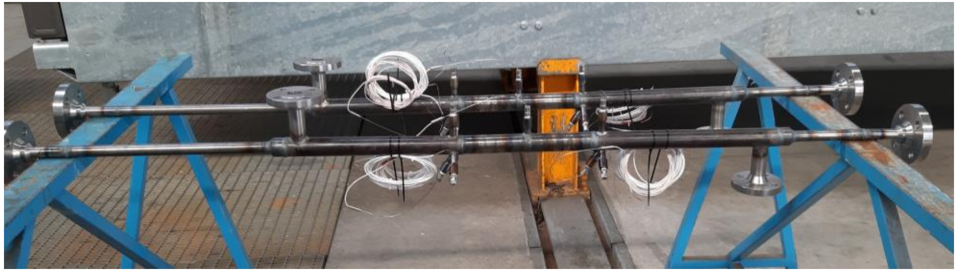


- The inner fins geometry and performance depends on four parameters
    - Fin number n
    - Fin heigh h
    - Fin thickness e
    - Fin helix angle α
- In literature, some tests have been conducted with small diameter tubes (from 3 mm to 15 mm) and none with blended CO_2
- For full scale installation with high mass flow, such small diameters would create too much pressure drop. In this case, most economical solution for air cooled condenser is 1’’ tubes (25,4 mm)
- Efficiency of fins are directly linked to the tube diameter

↳ As part of SCARABEUS project, tests have been organised with 1’’ tubes with the support of Technishe Universität Wien (TUW)

Test tube section : principle

- 3 differents test section have been tested :
  - plain tube (no inner fins) for reference
  - tube with a dedicated geometry for CO_2 gas cooling
  - tube with a dedicated geometry for CO_2 condensation
- Tests have been conducted with pure CO_2 and a blended CO_2 (CO_2 + R1234ze)
- Tube have been instrumented with sensors in order to calculate the local heat transfer coefficients (and pressure drop)



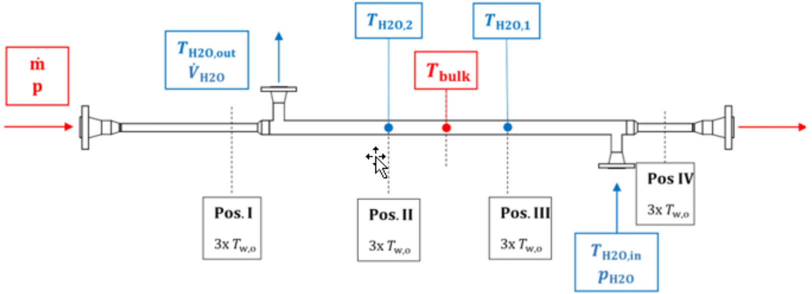


Figure 1: schematic of current test tube for heat transfer measurements when cooling and condensing; red…working fluid, blue…water, black…wall temperature.

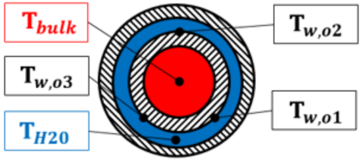


Figure 2: position of the temperature sensors at the cross section of the current test tube.

Test tube section : results

- For plain tube, the experimental HTC of the CO_2+R1234ze mixture fit very well with the ones calculated by Cavallini corrected by the Bell-Ghaly approach: most of the data points are within a range of ±10 %.

- For CO_2 condensation with inner fins, the improvement on HTC compared to plain tube can reach +40% for a pressure drop increase of 50 %.

- The improvement ratio is variable depending of the vapor content and the mass flux.

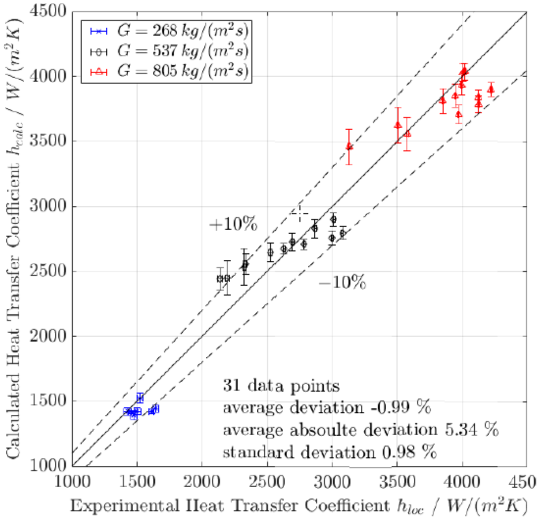
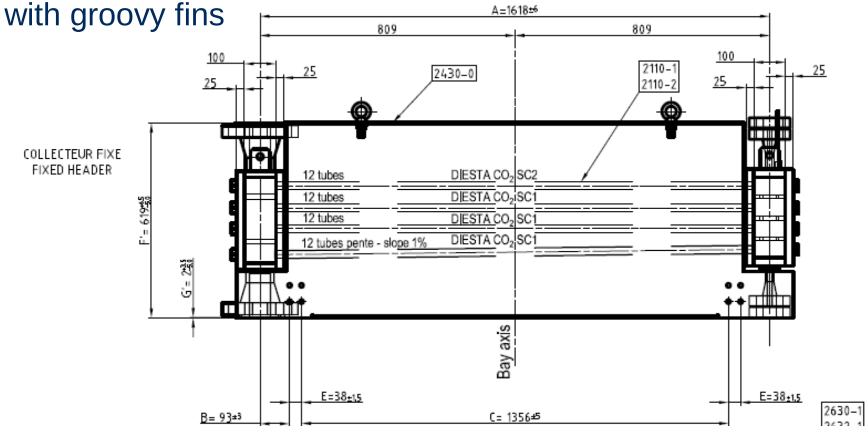


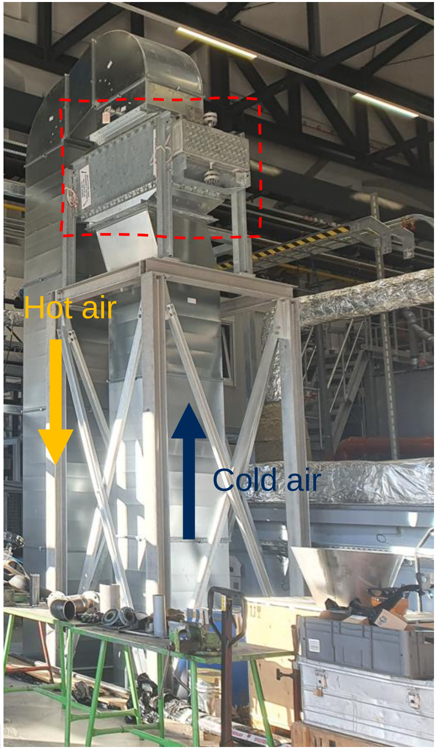
FIGURE 3: COMPARISON OF EXPERIMENTAL TO CALCULATED HEAT TRANSFER COEFFICIENTS OF THE MIXTURE CO_2+R1234ze(E).

Illyés *et al*., Design of Air-cooled condenser for CO2-base mixtures: model development validation and heat exchange gain with internal microfins - ASME Turbo Expo 2022 - Rotterdam

Prototype

- A prototype has been manufactured and will be tested in TUW in 2023
- Design : 4 rows / 4 passes
- Operating conditions : 87 bar g / 152 °C with blended CO_2
- First passe with dedicated inner fins for gas cooling (DIESTA CO_2 SC2)
- Others passes with dedicated inner fins for CO_2 and CO_2 blend condensation (DIESTA CO_2 SC1)
- Air side : enhancement with groovy fins





Full scale savings

	Standard ACC	Kelvion technology	Unit	Savings
Total Duty	235	235	MW	-
Ambient air	36	36	°C	-
Number of fan	3	3	per bay	-
Fan diameter	17	17	ft	-
Tube length	18.3	18.3	m	-
Number of tube per bay	413	413	-	-
Number of bay	19	16	-	-15.8%
Total price including 33% VSDS	6,745,000	5,460,000	€	-23.5%
Price per bay	355,000	341,250	€	-3.9%
Total weight	1302	1080	Tons	-20.5%
Fan total consumption	2451	2304	kW	-6%

Conclusion : The combination of new inner fins and groovy fins on airside allows to reduce the plot plan, the CAPEX, the OPEX and the carbon footprint.

Thank you for your attention