R&D activities on sCO_2 in Europe: Components Challenge – Heat Exchangers [2]

Primary heaters

Fourth episode – 12 June 2023


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Webinar content & speakers

- **CFD-aided conceptual design of a cooler in sCO_2 cycles** for novel waste-heat-to-power (WH2P) plant layouts (Panagiotis Drosatos – CERTH)

- **Development of a high-efficiency particle-sCO_2 heat exchanger for CSP applications** (Maxime Rouzès – John Cockerill)

- **How additive manufacturing will help the energy sector:** application to the primary heat exchanger in a sCO_2 cycle (Damien Serret - TEMISTH)

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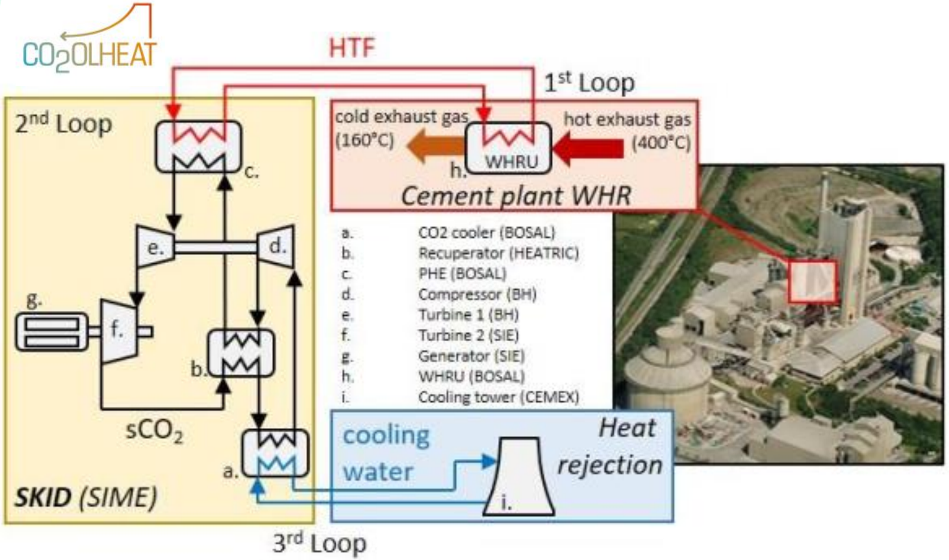
R&D activities on sCO_2 in Europe

CFD-aided conceptual design of a cooler in s-CO_2 cycles for novel waste-heat-to-power (WH2P) plant layouts

PhD(c) Panagiotis Drosatos, Research Associate at **CERTH**

CERTH
CENTRE FOR RESEARCH & TECHNOLOGY HELLAS

Problem description



The project CO_2OLHEAT (*Supercritical CO_2 power cycles demonstration in Operational environment Locally valorising industrial Waste Heat*)
has received funding from the European Union's Horizon 2020 research and innovation programme under **grant agreement N° 101022831**

- CO2OLHEAT project aims to demonstrate at **MW scale** a compact and efficient **sCO_2 cycle** for **WH2P application**

- CERTH provides support to industrial partner for the verification and optimization (if needed) of the **cooler design** in terms of thermal behavior and performance by using **CFD analysis** in ANSYS Fluent®

Problem description

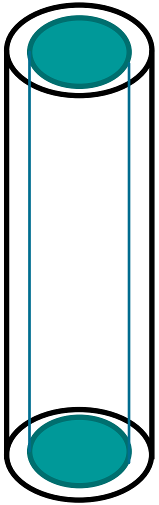
- In fact, cooler is a two-stream h/x; the interior domain consists of the working medium (s-CO_2), while the exterior of the cooling medium (water)
- The initial design* of the cooler h/x comprises **two cells** with **40 rows** of **4 U-tubes** each
- It also presents two headers, one for the inlet and one for the outlet flow
- Challenges in numerical simulation due to complicated geometric configurations

* Not allowed to be disclosed

Problem description

- When NIST real-gas libraries are utilized in an ANSYS Fluent® case, all domains need to include the **same medium**. If this is not the case, as in cooler h/x, each domain is represented by a different model . Both are **coupled** with each other **through a BC** (i.e., temperature distribution) on a common interface → challenge in numerical simulation

- **One half-cell** is simulated
- **Headers** are **excluded** from the first numerical tests (**homogeneous** distribution)



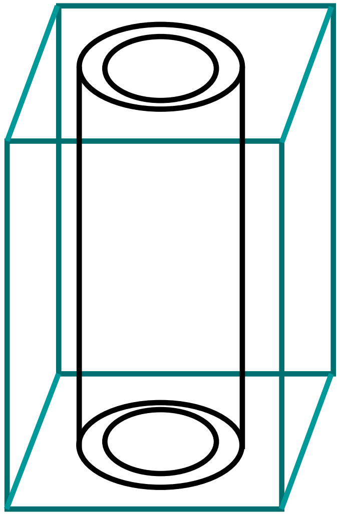
Domain 1 periodically sends to Domain 2 a profile of the temperature distribution on the interior surface of the tube

→

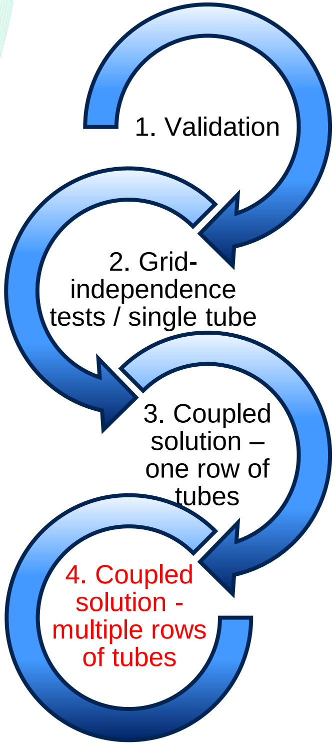
The overall solution is finalized when both solutions are converged

←

Domain 2 sends its feedback to Domain 1 as a profile of the temperature distribution on the exterior surface of the tube



Methodology



Proposed methodology

1. **Validation** of the **NIST properties** for the sCO_2 and the **models** provided in ANSYS Fluent® v15.0 using the **experimental data**[1] regarding the **thermal stratification in heated horizontal sCO_2 pipe flows**

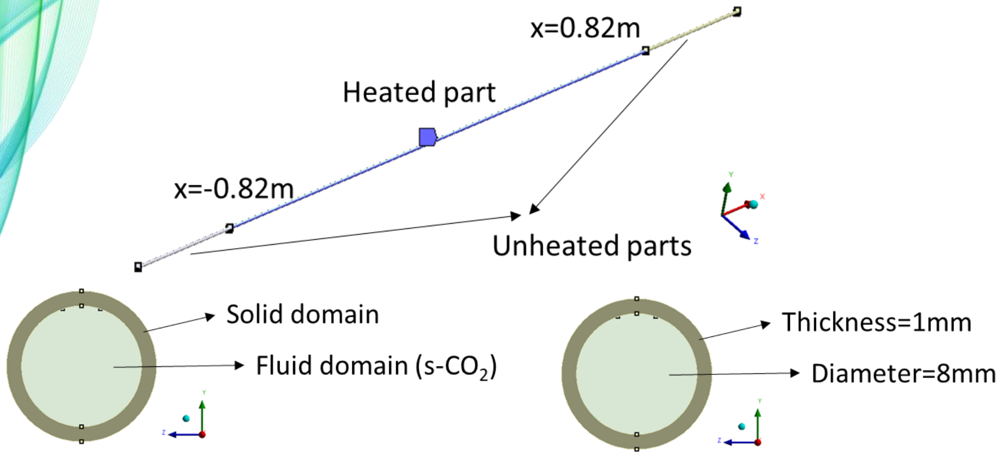
2. **Grid-independent solution**

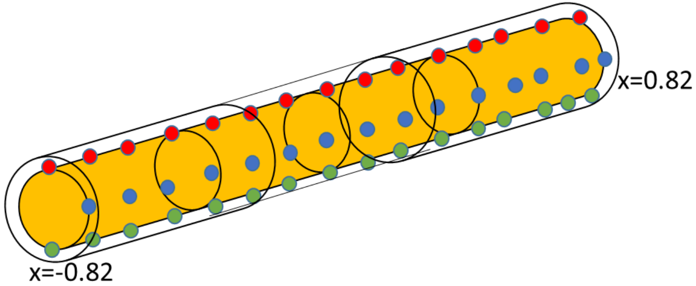
3. **Coupled scheme** in only **one row** of tubes

4. **Coupled scheme** in **multiple rows** of tubes, **if possible**

[1] Experimental investigations on the heat transfer characteristics of supercritical CO_2 in heated horizontal pipes, K. Theologou, et al. , The 4th European sCO_2 conference for energy systems, March 23-24, 2021

Validation - Experiment

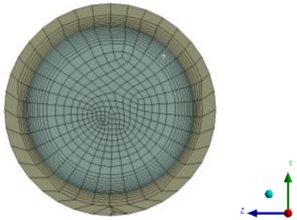
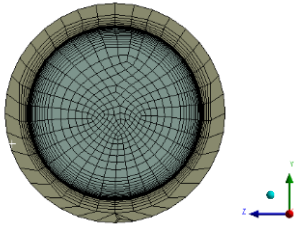
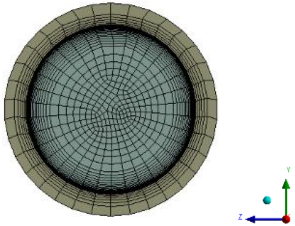
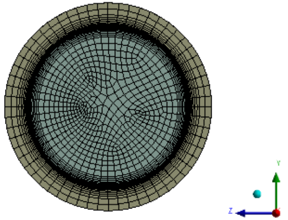




Properties	Value
Thermal conductivity of the tube's material (W/m/K)	11.4
Heat flux on the exterior side of the tube's heated part (kW/m^2)	104.
Inlet mass flow rate, temperature and pressure	0.04 kg/s or 800 kg/s/m^2 5^{o}C 77.5 bar
Conditions on the exterior side of the tube's unheated parts (BCs)	convection heat transfer coefficient = 10 W/m^2/K free stream temperature = 20^{o}C

- During the **experiment**, **42** points on the **top**, **42** on the **bottom** and **42** on the **side** of the tube were used to measure the **wall temperature**
- This parameter (**metal temperature**) along with the **working medium enthalpy** will be used for the mathematical model **validation**.

Validation – Numerical grids

	Numerical Grid #1	Numerical Grid #2	Numerical Grid #3	Numerical Grid #4
Inflation layers on fluid and solid part	fluid:10, solid:5	fluid:20, solid:5	fluid:40, solid:5	fluid:40, solid:5
Edge sizing	Inner edge:34 Outer edge:36	Inner edge:34 Outer edge:36	Inner edge:34 Outer edge:34	Inner edge:60 Outer edge:60
Number of divisions along the flow (heated part)	300	300	2400	2400
Number of cells	611,200	867,510	5,257,275	9,642,216
Element size (global), min/max (m)	1.84e-04 – 1.43e-03	1.21e-04 – 1.43e-03	3.61e-05 – 9e-04	2.47e-05 – 6.29e-04
wall Y+ (interface), min/max	6.06 – 26.62	1.11 - 4.63	0.027-0.108	0.017-0.057
Depiction of the developed grid (side view)				

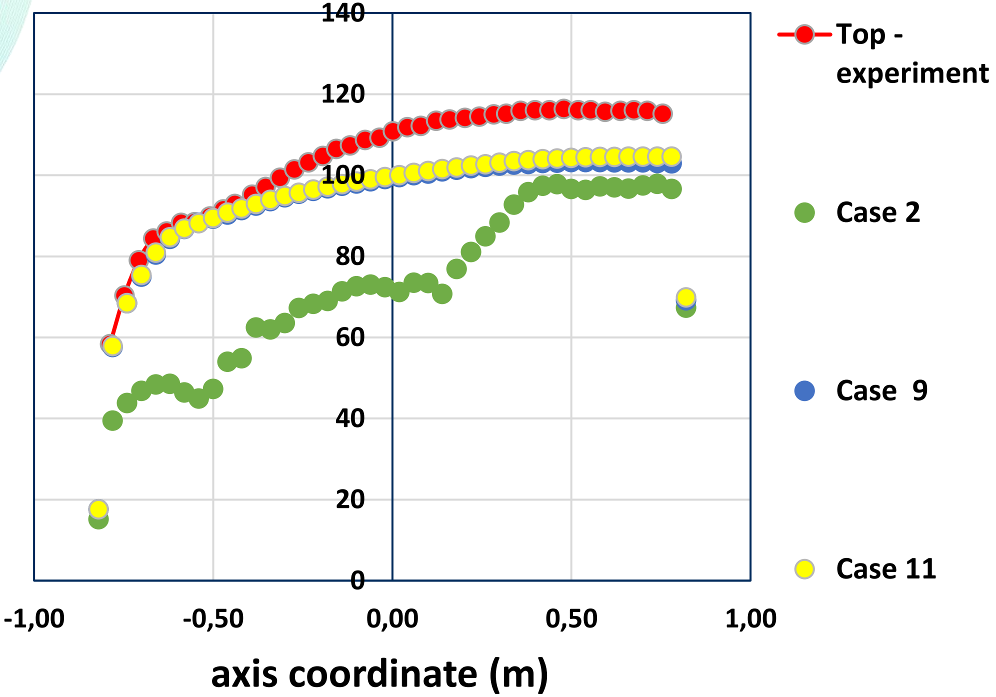
Validation – Parametric investigation

Among the several tests performed the ones with special interest are:

	Turbulence model	Spatial discretization	Numerical Grid	Scope
Case 2	SST k-omega	• Green-Gauss Cell-Based • Standard scheme for pressure discretization • Second Order Upwind scheme	Numerical Grid #1	Examination of the **effect of the numerical grid** on the results derived by the **SST k-omega** turbulence model
Case 9	SST k-omega	• Green-Gauss Cell-Based • Standard scheme for pressure discretization • Second Order Upwind scheme	Numerical Grid #3	
Case 11	SST k-omega	• Green-Gauss Cell-Based • Standard scheme for pressure discretization • Second Order Upwind scheme	Numerical Grid #4	

Validation – Results

Wall temperature (°C) on the top



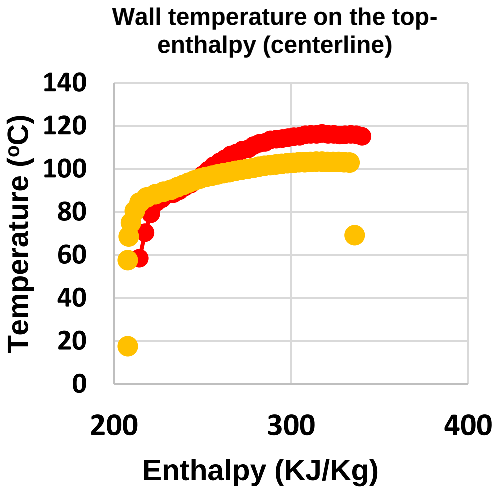
- The **SST k-omega turbulence model** with **coarse mesh** (Numerical Grid #1) **cannot provide satisfactory agreement** with the experimental data, see Case 2

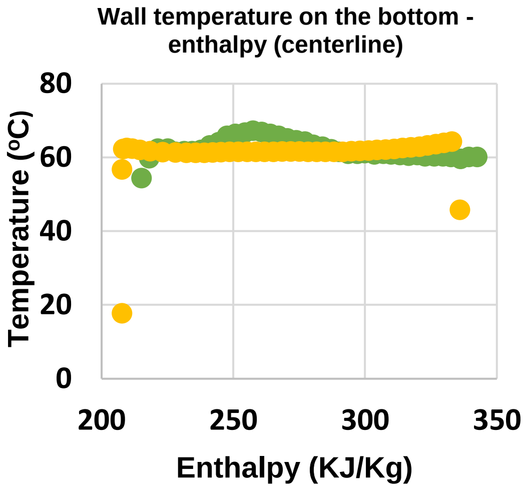
- The **SST k-omega turbulence model** with **middle** (Numerical Grid #3) and **dense** numerical grid (Numerical Grid #4) **provides better agreement** with the experimental data, see Case 9 and Case 11 → necessity for high computational resources; further challenge in numerical simulation

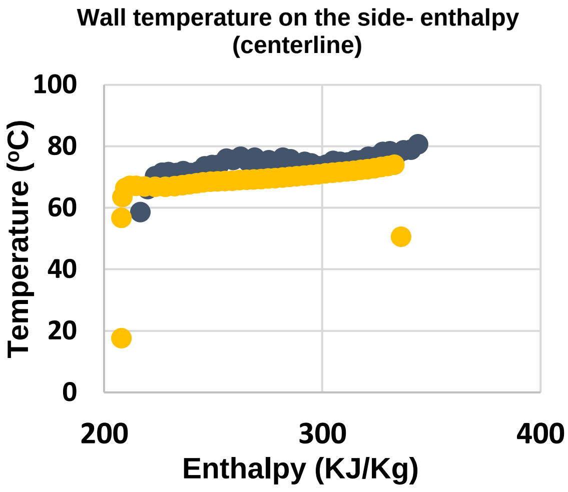
- There is **grid-independent solution**, based on the comparison of two cases with different grid discretization, Cases 9 & 11

- The selection of **different turbulence model deteriorates** the results, **despite** the implemented **grid density**

Validation – Results



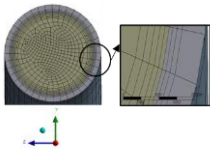
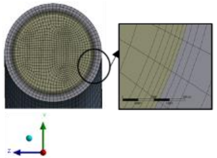
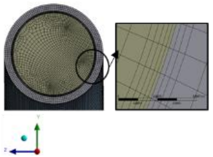
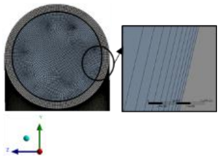




CFD results

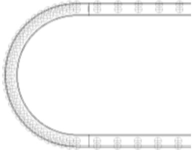
- The results derived by the ANSYS Fluent® in the case of **SST k-omega** turbulence model with **middle numerical grid** in terms of wall temperature/working medium enthalpy distribution along the working medium flow direction present a very satisfying **agreement** with the **experimental data**, especially for the **side** and **bottom** points of the tube

Grid independence – Cases & numerical grids

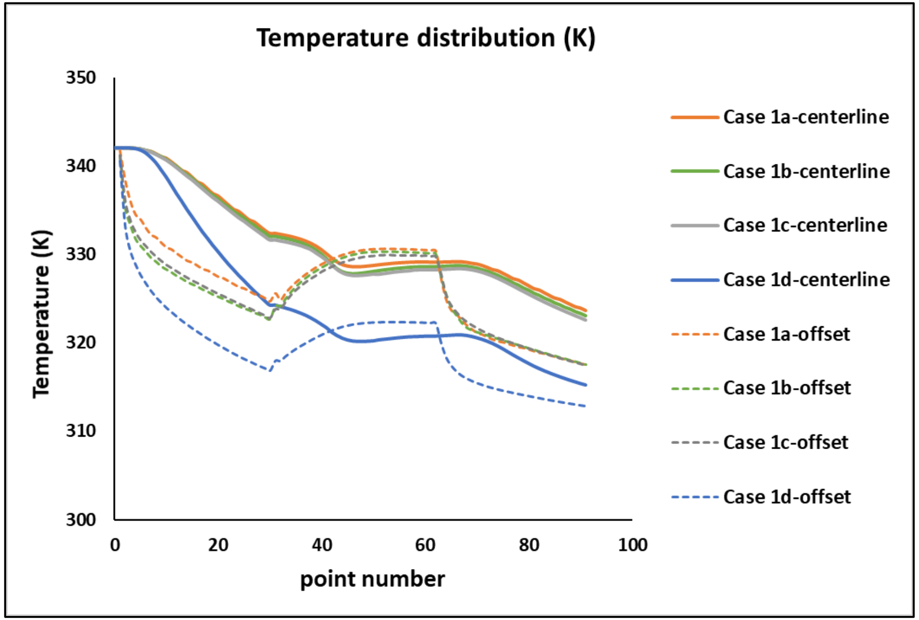
	Case 1a	Case 1b	Case 1c	Case 1d
Domain	5 interior & 3 exterior inflation layers 	5 interior & 3 exterior inflation layers 	5 interior & 3 exterior inflation layers 	10 interior & 5 exterior inflation layers 
Total number of elements	112,000 hexa	480,555 hexa	2,125,530 mixed	14,086,800 hexa
Maximum skewness factor / interior wall y+	0.61 / 95.32-222.59	0.51/ 40.95-115.07	0.60/ 20.19-59.12	0.88/ 0.30-0.72

The imposed conditions are the ones of the real operation

Grid independence – Results

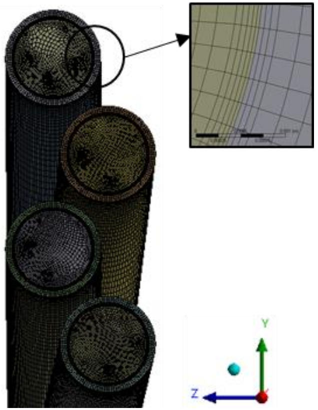
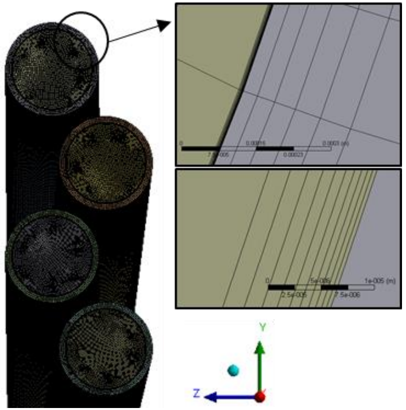


Temperature distribution in **two** groups of **91** points each; the first **along** the tube **centerline** and the second close to the tube **interior surface**



- The **first three** cases, **despite** the different **grid quality**, show agreement to each other, both for the centerline and the boundary points
- When, however, a sophisticated grid close to the domain boundary is applied, Case 1d, **y+ values <1**, significant **differences** can be seen.
- For **higher accuracy** of the derived results, special attention must be paid to the development of the **boundary layers**, owing to the implementation of the **k-omega SST turbulence model**. So, highest **y+** values must be **below 1**

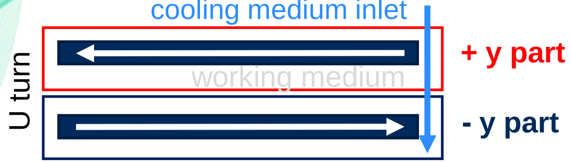
Coupled scheme (1 row) – Cases & numerical grids

	Case 2a	Case 2b & 2c & 2d & 2e
Domain (interior)	5 interior & 3 exterior inflation layers 	10 interior & 5 exterior inflation layers 
Total number of elements	7,721,865 mixed	24,640,800 hexa
Maximum skewness factor / interior wall y+	0.93 / 16.53-94.00	0.98 / maximum <1

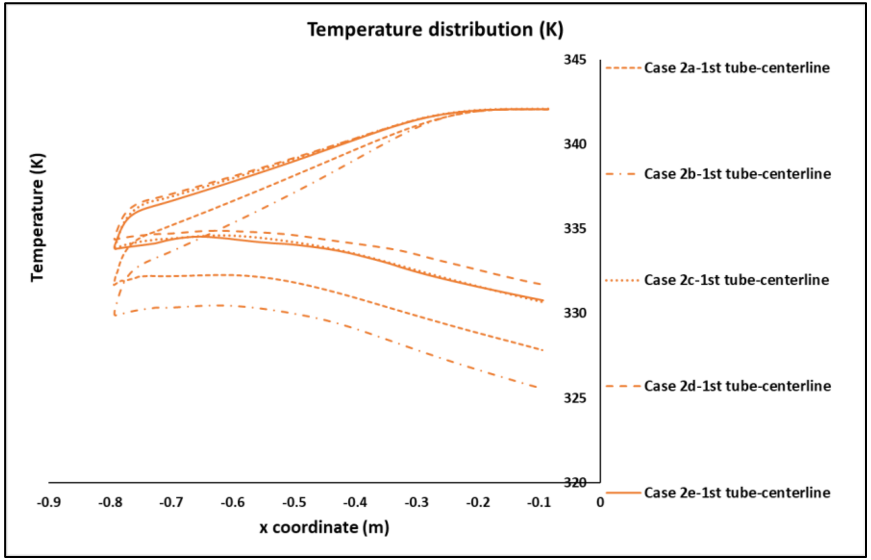
Coupled scheme (1 row) – Cases & numerical grids

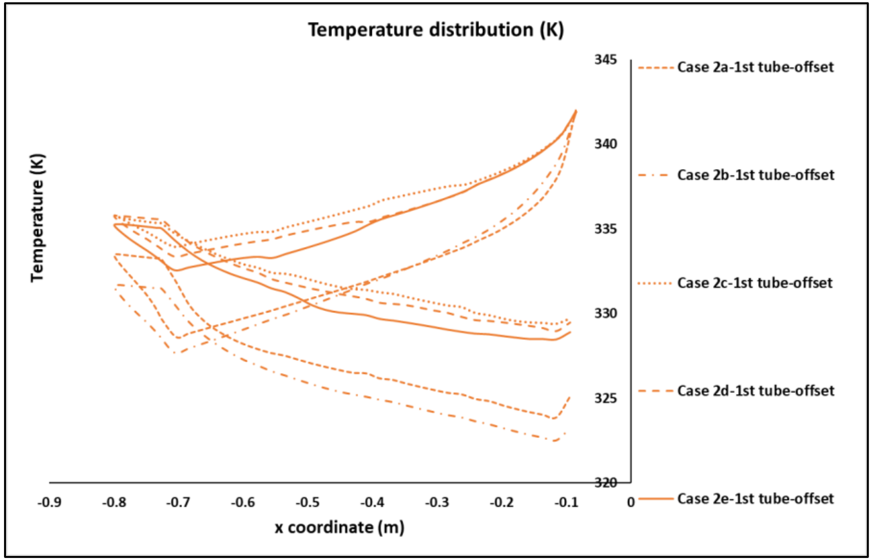
	Case 2a	Case 2b	Case 2c	Case 2d	Case 2e
Domain (exterior)	5	5	10 interior 10 exterior (9.62e-06m max thickness)	10 interior 10 exterior (7.62e-06m max thickness)	10 interior 10 exterior (5.62e-06m max thickness)
Total number of elements	6,407,215 mixed	747,072 mixed	11,630,695	17,989,526 mixed	25,852,600 mixed
Maximum skewness factor / interior wall y+	0.82 / 0.22-52.18	0.91/ 0.26-166.68	0.79/ <1	0.99/ <1	0.83/ <1

Coupled scheme (1 row) – Results



Temperature distribution in 184 points for the first tube (92 for the centerline and 92 for the points close to the wall) and 112 points for the rest tubes (56 for the centerline and 56 for the points close to the wall)





Among all four tubes, in each case examined, the **differences** in the **temperature distribution** are **minor**

Coupled scheme (1 row) – Results

- Close to the tubes' **boundary walls**, in the **U-turn formation**, **temperature increase** of the working medium is observed owing to the adiabatic BC (zero heat losses) and the resulted higher material temperature

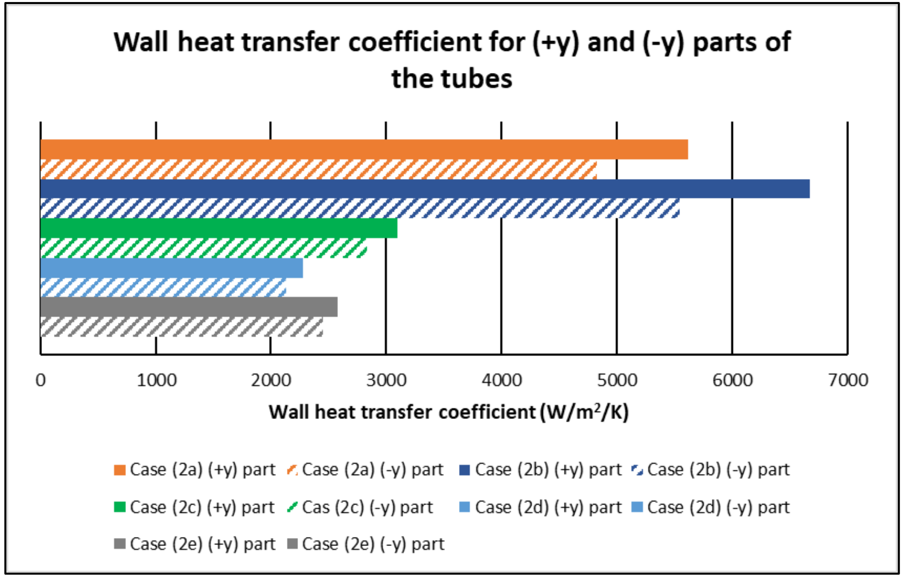
- On the contrary, in the same region, along the **tube's centerline,** the trend of **gradual temperature decrease** is observed

- **Steeper temperature decrease slope** in the first part of the tube **(+y part).** This indicates **higher heat transfer rates** in this specific region, owing to the **lower** temperature levels of the **inlet water stream**

- The small differences among the four tubes for each case **indicate homogeneous field of the heat flux density values**

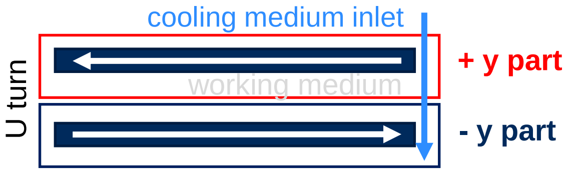
- In fact, **Case 2c, Case 2d and Case 2e (**all with **high grid density)** show **minor differences** between each other for all four tubes in terms of the working medium temperature distribution, since the **absolute temperature differences are <5^{o}C**

Coupled scheme (1 row) – Results

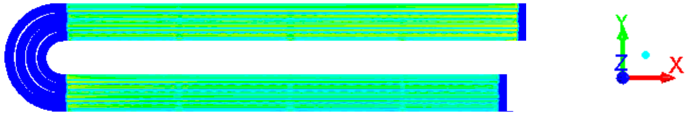
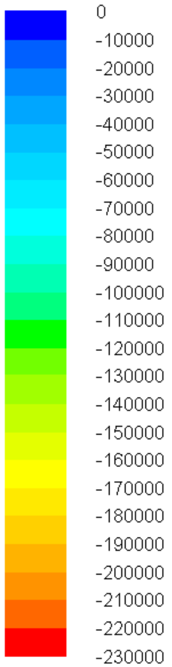
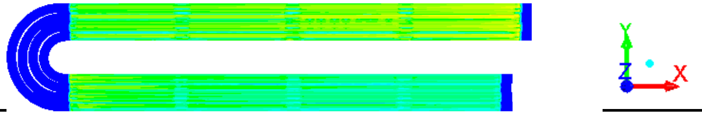
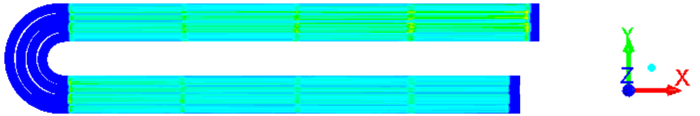
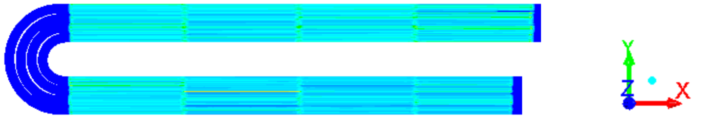
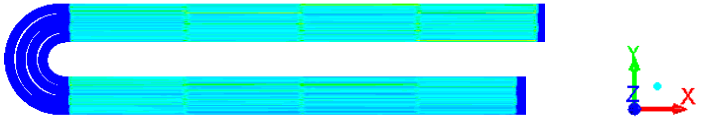


Wall heat transfer coefficient (W/m²/K)	Case (2a)	Case (2b)	Case (2c)	Case (2d)	Case (2e)
+y part	5616	6676	3097	2282	2583
-y part	4826	5548	2837	2133	2452

- **Higher heat transfer rates** in +y region, owing to the **lower** temperature levels of the **inlet water stream**
- Differences among the cases. The **impact** of the developed **numerical grid** on the results is **significant**



Coupled scheme (1 row) – Results

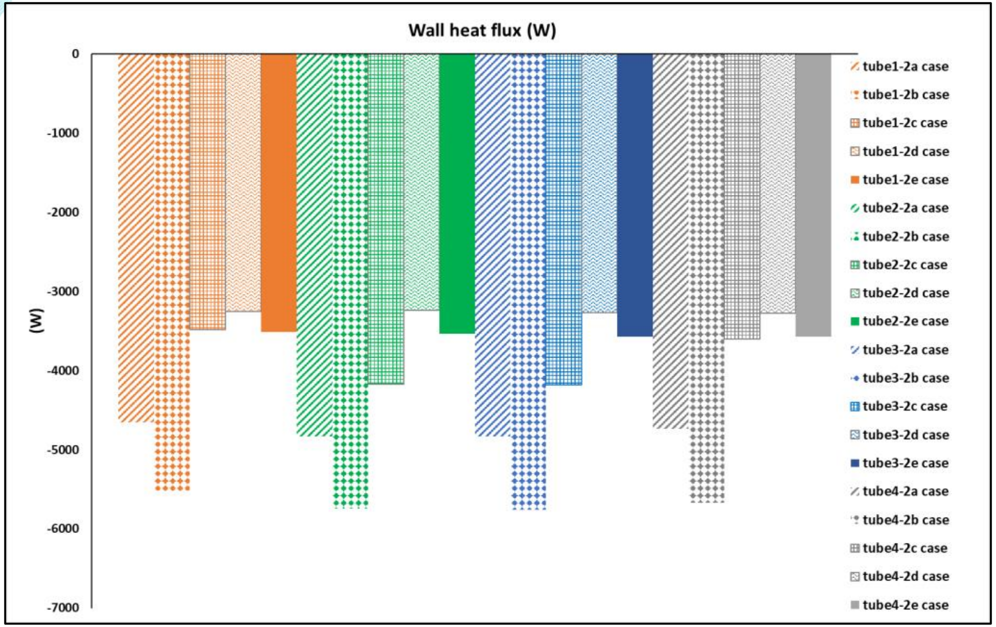
Case	Heat flux density	Legend (W/m²)
Case(2a)		
Case(2b)		
Case(2c)		
Case(2d)		
Case(2e)		

- **Homogeneous heat flux** density field among the **four tubes** for each case considered

- Cases 2c, 2d and 2e (all with **high grid density**) show minor differences between each other

Coupled scheme (1 row) – Results

Significant differences even in only one row of tubes among the cases. **Smaller differences** observed in Cases 2c, 2d and 2e (all with **high grid density**)



(w)	Case (2a)	Case (2b)	Case (2c)	Case (2d)	Case (2e)
Tube 1	-4654	-5519	-3484	-3249	-3512
Tube 2	-4828	-5740	-4170	-3241	-3535
Tube 3	-4833	-5755	-4181	-3268	-3570
Tube 4	-4738	-5668	-3602	-3272	-3572
Total	-19053	-22682	-15437	-13030	-14189

Estimation for all rows of tubes from **extrapolation**: based on CFD simulations, in this case for example, the heat transfer for 40 rows of U-turn tubes is expected to be **0.52MW-0.62MW**

Coupled scheme (1 row) – Conclusions

- The validation process indicated that a **very fine grid** (y+<1) with **k-omega turbulence model** provides the **best agreement** between experimental data and CFD results

- Therefore, the simulation of the cooler h/x has been proven **quite challenging**

- High **demands on computational resources → 60-80 cores** for each domain

- The investigation was forced to be focused on **only one row** of tubes

- **No grid-independent solution** was able to be achieved. There is need for very dense grid to reduce the differences among the derived results (y+ <1)

- Due to **computational resource limits**, the overall performance (all rows of tubes) can only be estimated by **extrapolation** of the results as derived by only one row of tubes

- In similar cases, CFD model needs **experimental data** for further calibration and validation

Challenges in the numerical simulation

Thank you for your attention!

The project CO2OLHEAT (*Supercritical CO_2 power cycles demonstration in Operational environment Locally valorising industrial Waste Heat*)
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R&D activities on sCO_2 in Europe

Development of a high-efficiency particle-sCO_2 heat exchanger for CSP applications, Maxime Rouzès, John Cockerill

Outline

- John Cockerill Solar & Thermal storage
- COMPASsCO2 project
- Industrial-scale Particle-sCO2 Heat Exchanger (HEX)
- Challenges
- Conclusion & Perspectives

John Cockerill Solar & Thermal Storage

"200-year expertise in boiler engineering at disposal for CSP development"

Innovation
- New concept
- *Development*
- Design

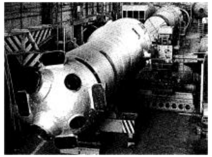
Realization
- Optimization
- *Validation*
- Manufacturing

Installation
- Assembly
- Inspection
- Monitoring

- ✓ 2012: First solar receiver.
- ✓ 2012: First HRSG with stainless steel
- ✓ 2014: First Molten Salt Solar Receiver
- ✓ 2019: Molten Salt Steam Generator
- ✓ 2022 : Molten Salt Solar Receiver

1817 → now

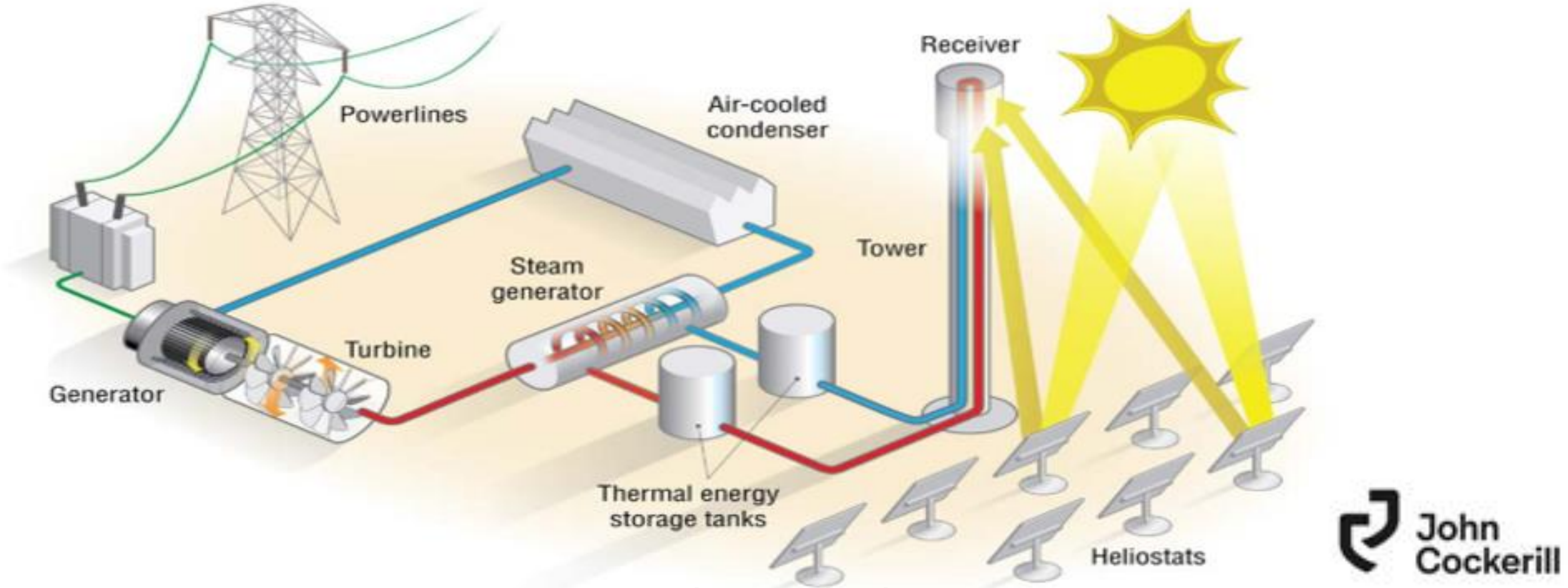







John Cockerill Solar & Thermal Storage

Concentrated Solar Power Plant (CSP)



Source : John Cockerill

John Cockerill Solar & Thermal Storage

Molten Salt Solar Receiver

Source : John Cockerill, DEWA Power plant, Dubaï, UAE

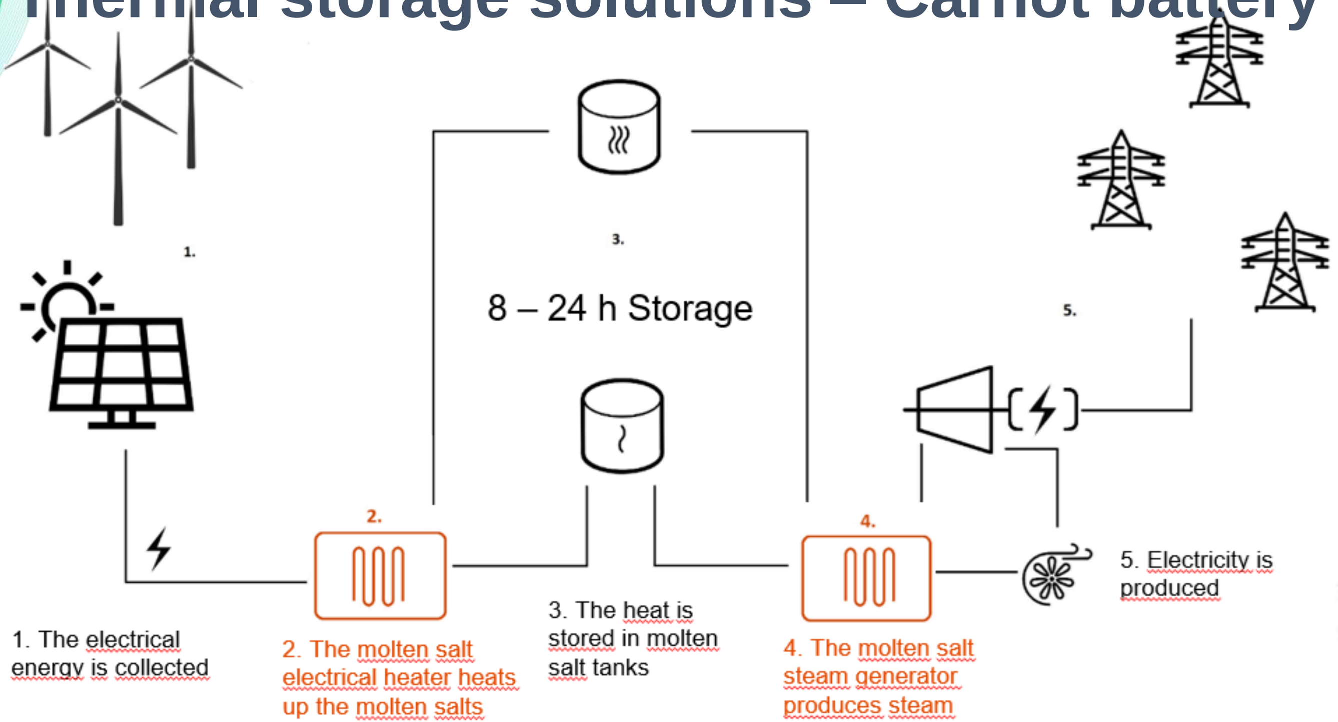
John Cockerill Solar & Thermal Storage

Molten Salt Steam Generator

Source : John Cockerill, Molten Salt Steam Generator 3D model

John Cockerill Solar & Thermal Storage

Thermal storage solutions – Carnot battery

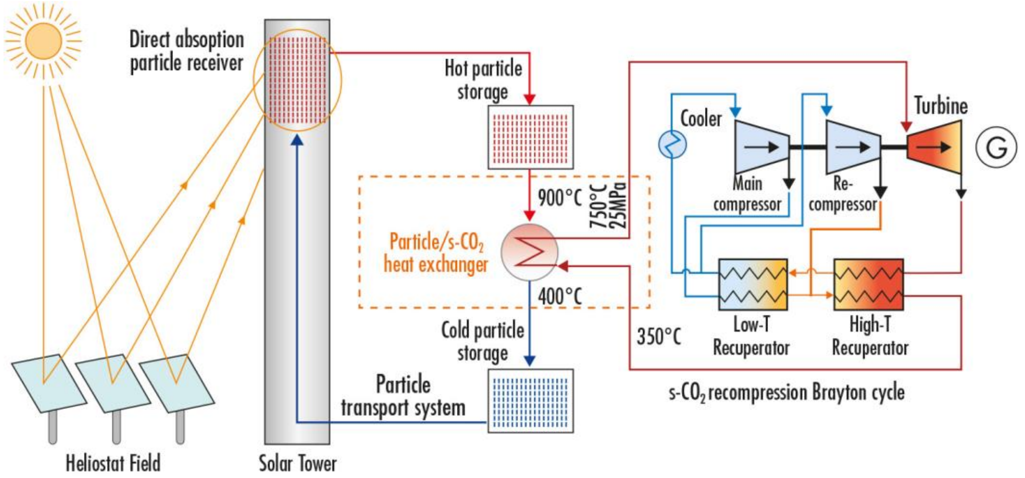


COMPASsCO2

Objectives

The project focus is to develop **new materials for extreme conditions** in order to integrate two innovative systems:

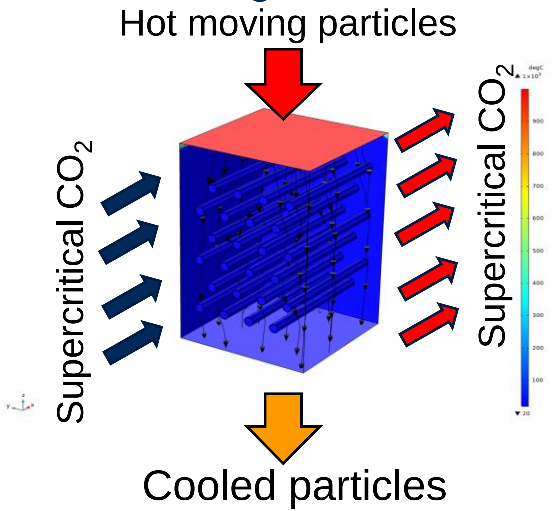
CSP plants with particles and sCO2 Brayton power cycles



COMPASsCO2

John Cockerill Solar scope

Design, construct and operate a 40 kW particle/sCO2 heat exchanger section in order to validate the degradation and heat transfer models



COMPASsCO2

Particle-sCO2 HEX

Process parameters

Parameters	Particles (high pressure HEX)	sCO2 (high pressure HEX)
Inlet temperature [°C]	900	532,8
Outlet temperature [°C]	582,8	700
Inlet pressure [bar]	/	265,3
Outlet pressure [bar]	/	260
Mass flowrate [kg/s]	355,9	632,6

COMPASsCO2

Particle-sCO2 HEX : challenges

Process conditions

⇒ High power : ~ 130 MW

⇒ High temperature & gradient

⇒ High pressure

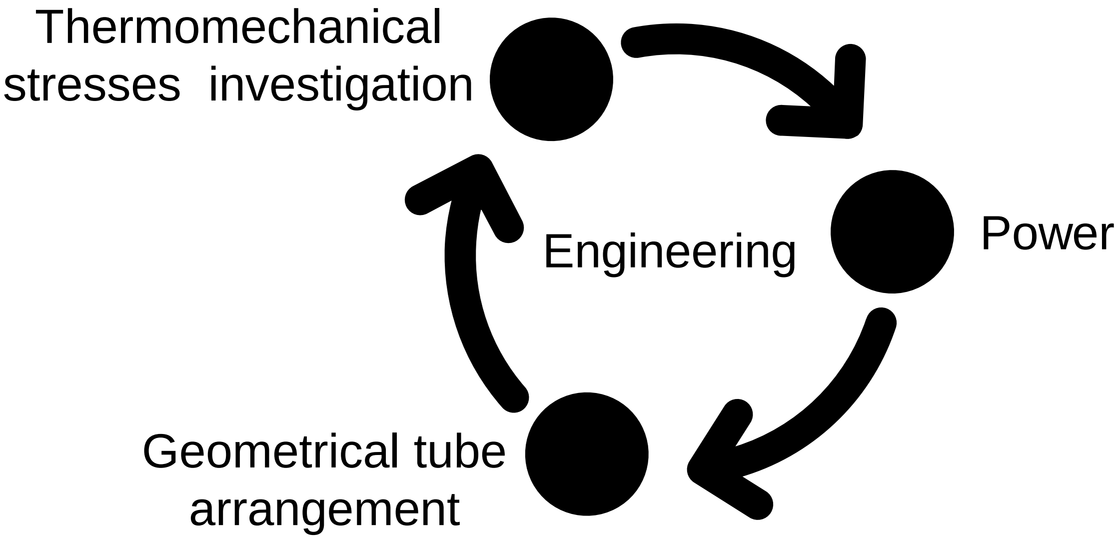
⇒ Corrosive & erosive environments

⇒ Material & cost

COMPASsCO2

Particle-sCO2 HEX : challenges

Design methodology & optimization

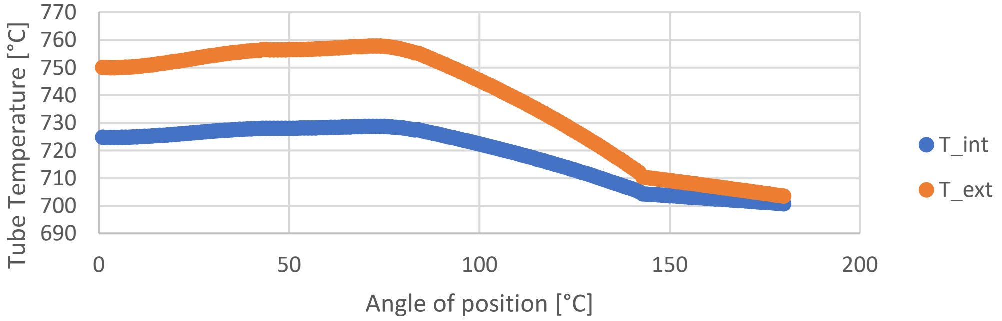


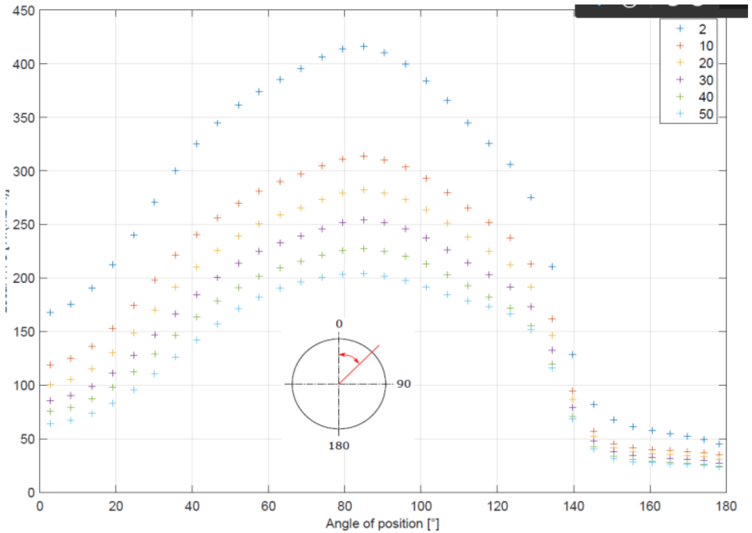
COMPASsCO2

Particle-sCO2 HEX : challenges

One example : the “Banana” effect

Temperature angular distribution along the most extreme tube





⇒ Non-homogeneous distribution of temperature along the most extreme tube

⇒ Angle-dependent particle heat transfer coefficient

COMPASsCO2

Particle-sCO2 HEX : challenges

Material selection

Material	Temperature limit	Pressure limit	Selected materials
Creep-strength enhanced ferritic and advance austenitic stainless steels	590°C < T < 620°C	250 bar	**P92** Sanicro 25
Ni-based alloys	700 °C < T < 750 °C	350 bar	**Haynes 282** Inconel 740 Inconel 617

COMPASsCO2

Particle-sCO2 HEX : challenges

Manufacturing

⇒Tailor-made tubes (high pressure)

⇒Material procurement

⇒Long lead time

⇒Weldings on site

- ⇒ Dissymmetric - heterogeneous
- ⇒ NDT
- ⇒ Accessibility

⇒ Hydrotests

Transportation

⇒ Height = 3,5m max.

⇒ Width = 4 m max.

⇒ Length = 25 m

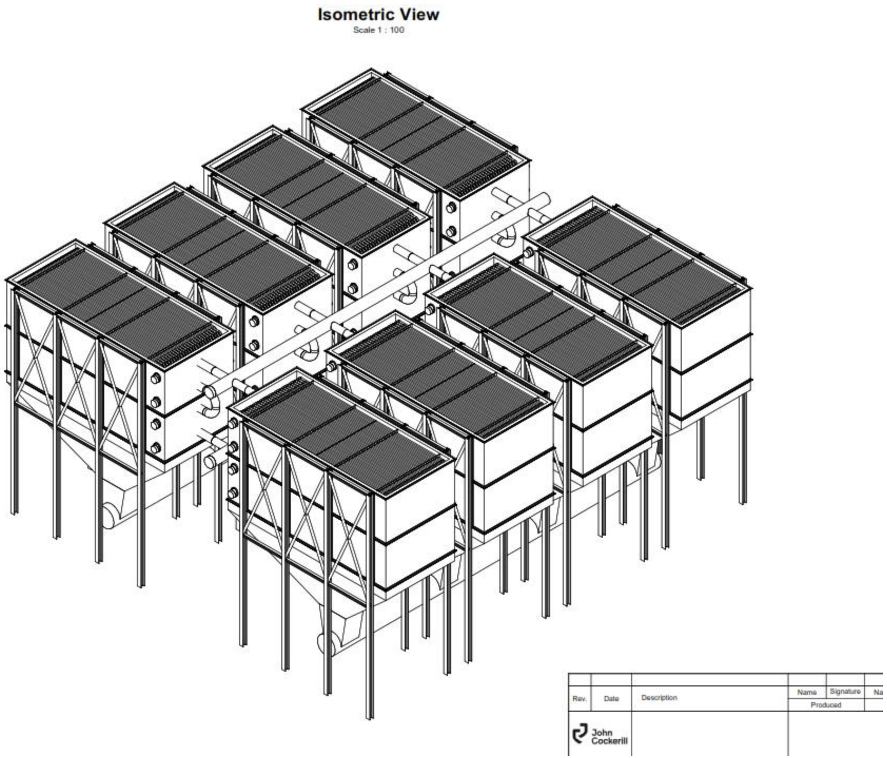
⇒ Weight = 50T-60T

⇒ Road surveys necessary

COMPASsCO2

Particle-sCO2 HEX

Modular Solution



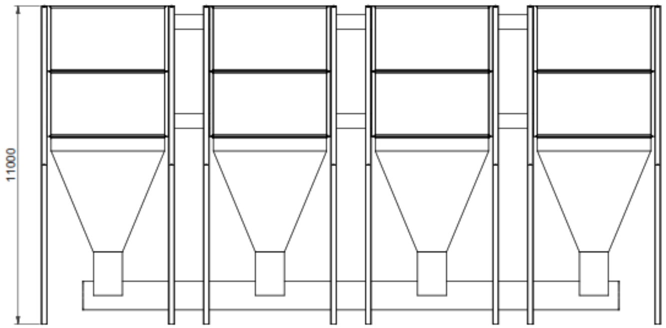
⇒ 2 materials (Ni-based alloys + P92 or Sanicro25)
⇒ Intermediate headers
⇒ Modules interchangeable

COMPASsCO2

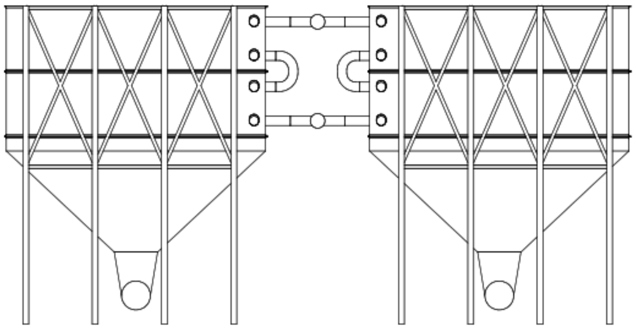
Particle-sCO2 HEX

Modular Solution

Front View
Scale 1 : 100



Left View
Scale 1 : 100



ETN sCO2 webinar series

Conclusion & Perspectives

- **Materials selection & cost**
- **Harsh environment (high pressure & temperature)**
- **Manufacturing, transportation & assembly**

- **New design : modular solution**
- **Lab-scale pilot tests**
- **Techno-economic optimization analysis**

Thank you for your attention

COMPASsCO2

The COMPASsCO2 project has received funding from the European Union's Horizon 2020 Research and Innovation Action (RIA) under grant agreement No. 958418.

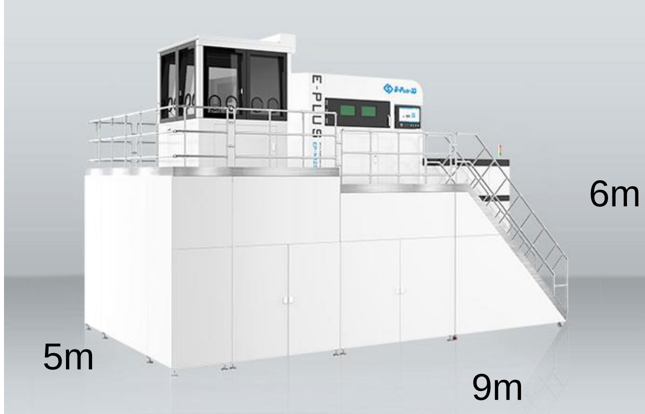
R&D activities on sCO_2 in Europe

How additive manufacturing will help the energy sector:
Application to the primary heat exchanger

Damien SERRET, R&D Manager
temisth

Introduction: Additive manufacturing

Part size limitations (L-PBF technology)



Volumes available are “limited”

Some “old” big 3D printer (Ref. 2018)

- X-Line (Concept Laser - US) 500 x 500 x up to 400 mm3
- MetalFAB 1 (Additive Industry - Nederland) 420 x 420 x 400 mm3
- TS500 (Techgine 3D – China) 500 x 500 x 1000 mm3

Some available big 3D printer (Ref. 2023)

- Saphire (Velo3D - US) 600*1000 mm^3
- M 4K-4 (AMCM – US) 450x450x1000 mm^3
- NXG XII (SLM Solution – Germany) 350 x 350 x 350 mm &12 lasers (up to 1000ccm/h)
- FS621M-U-4 (Farsoon – China) 620x620x1700 mm^3
- M1250 (Eplus3D – China) 1250x1250x1350mm^3 & 9 lasers

➔ AM HX size will still be bigger and bigger & faster and faster !

Outline

- TEMISTh company
- Additive Manufacturing for heat exchanger
- DESOLINATION project
- Primary heat échanger development

About us

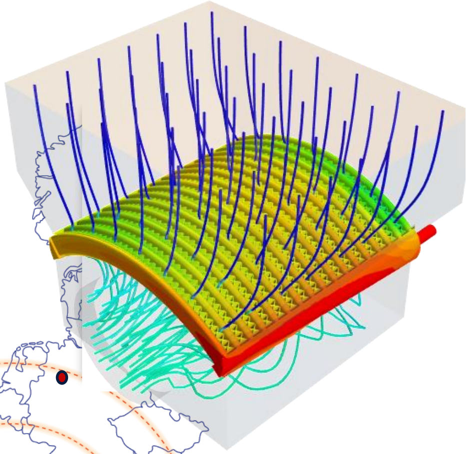
Our team of **experts in thermal systems and advanced manufacturing** supports industrial companies in the development of **tailored solution**:

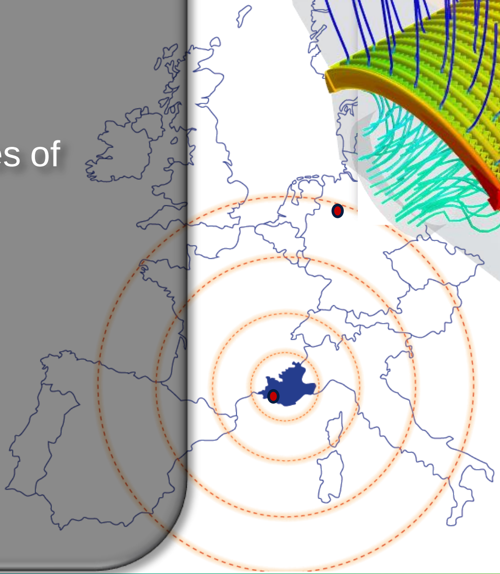
- Design and optimization
- Advanced manufacturing
- Testing and qualification

New : we are supplier of small batches of customized thermal parts

Domains of activity:

- Aerospace and defense
- Transports
- Energy
- Oil & Gas



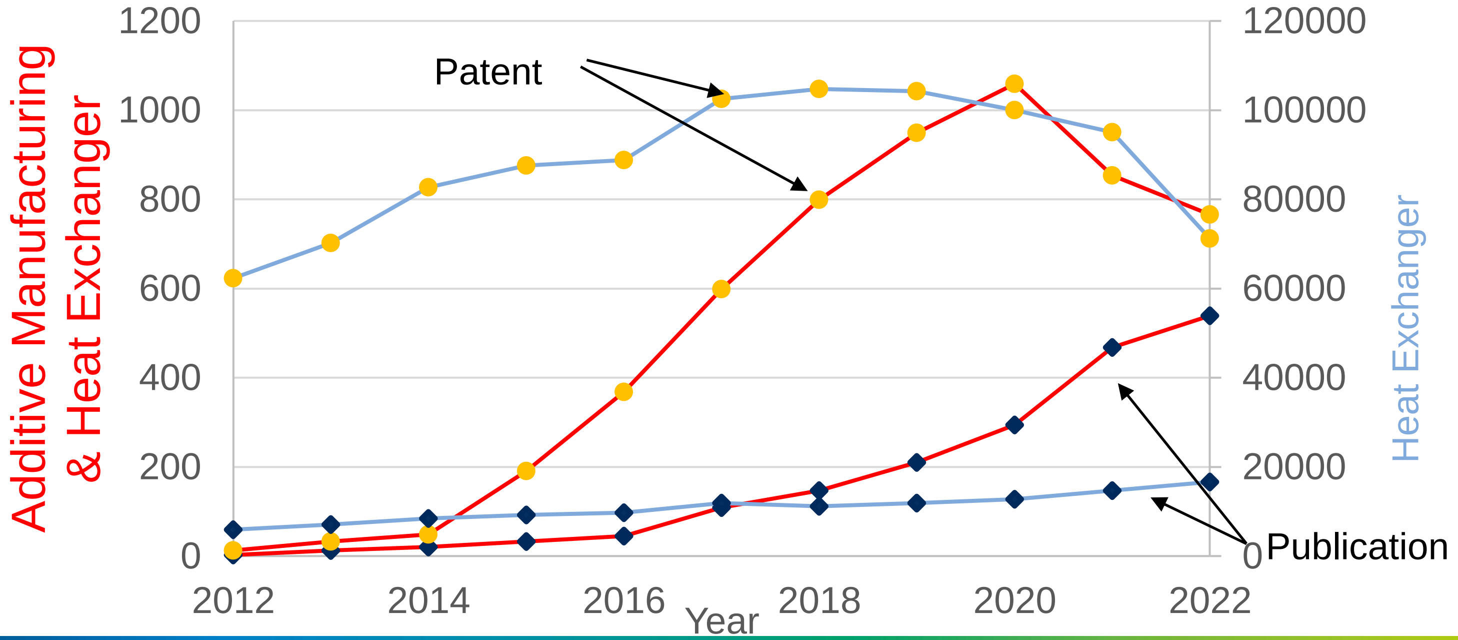


Domains & Applications

And anywhere thermal management is an issue …

Additive manufacturing

Additive manufacturing Impact on the HX area



Additive manufacturing

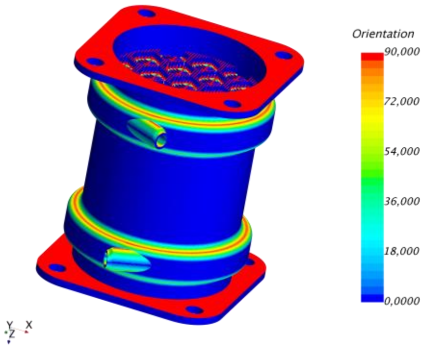
Additive manufacturing Impact on the HX area

A lot of industrial HX manufacturers involved on the topic:

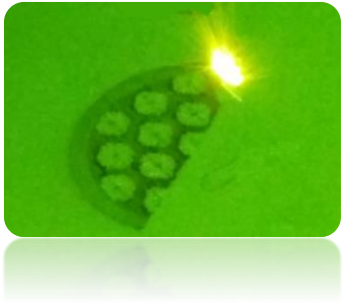
- Aeronautic: UTC, Raytheon, Safran, GE, Boeing, Airbus, Liebherr…
- Oil & Gas : Air Liquide, Linde
- Automotive : Valeo, Honda
- Energy : Westinghouse, CEA, Siemens Energy
- HX manufacturer: Alfa Laval, Fives Cryo, Meggit (Heatric & Hieta), Nexson…

Additive Manufacturing

How to take benefit from this manufacturing process ?



3D file



Additive Manufacturing

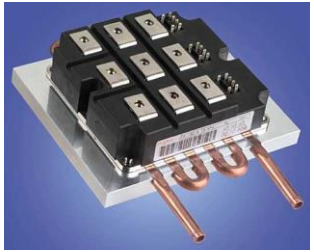
Real part

From virtual file to a materialized component

15 June 2023

Allow realizing complex internal structures
Allow reducing assembly
Parts can be modified and produced on demand

Heat exchangers at all sizes



Electronic cooling

Heat exchangers sizes

Power plant

Engine thermal management

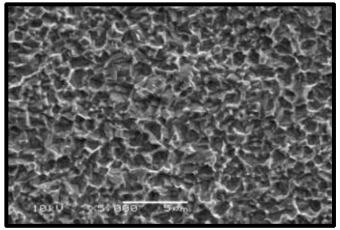
Primary HX case

Additive manufacturing

Mutiscale characterization

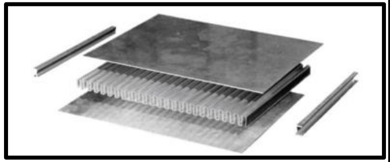
µm — mm — cm — dm

- Roughness



Copper surface roughness [1]

- Fin thickness
- Tube thickness
- Fin gap



Basic components of plate fin stack [2]

- Tube diameter

Finned tubes [3]

- HX volume
- Manifold

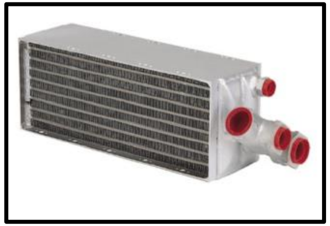


Plate fin Heat-Exchanger [4]

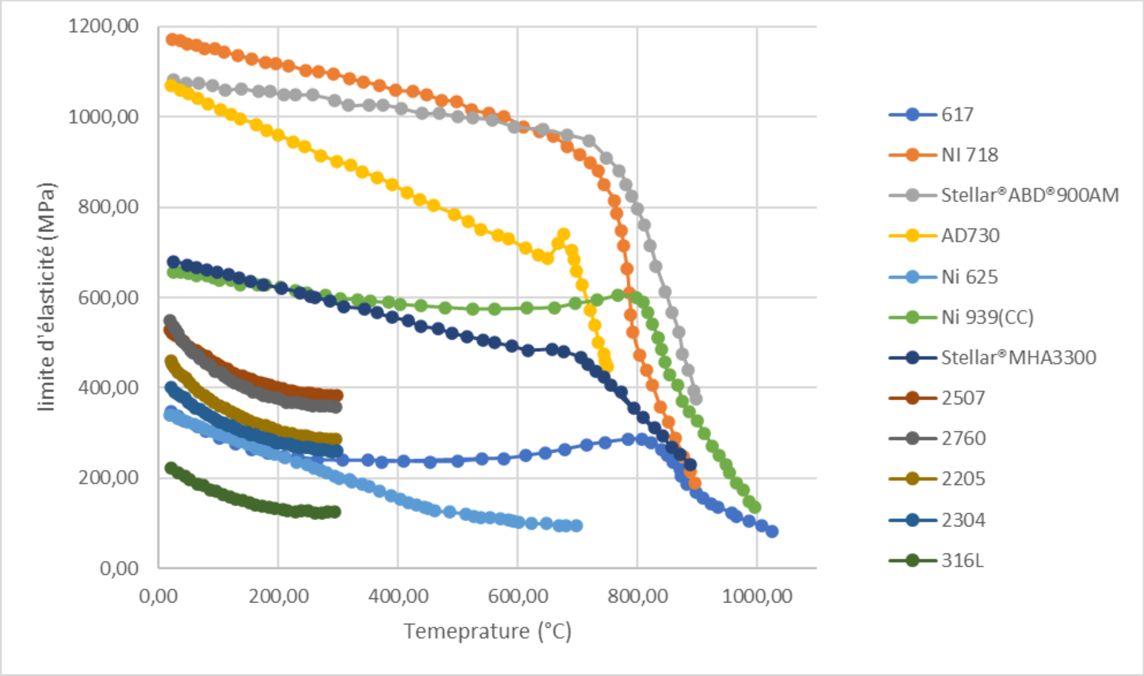
Ex: Impossible to design and simulate the HX performances at all scales

→ Choice to do considering the studied scale (roughness model, equivalent porous model…)

[1] TOSCANO, Lenora et LONG, Ernest. CONTROLLING COPPER ROUGHNESS TO ENHANCE SURFACE FINISH PERFORMANCE.
[2] Trane Company
[3] Baknor Cooling Company
[4] BOYD Corporation

Additive manufacturing

Material interest and comparison

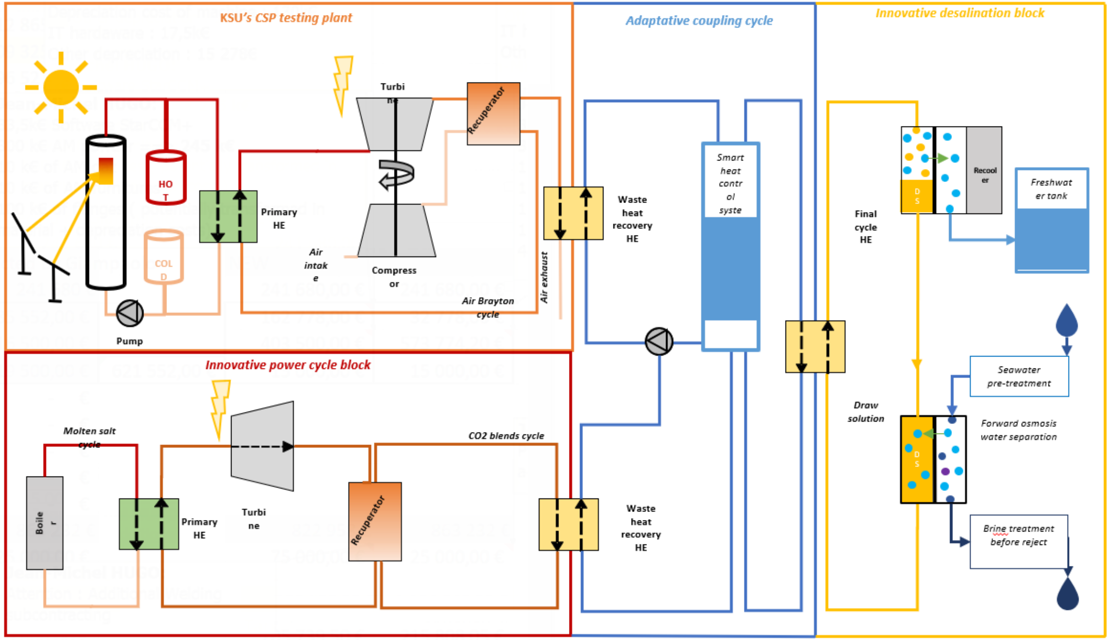


- NI 718 widely used in Aeronautic
- Interest to developp new alloys and set of AM parameters (Haynes alloys for example)
- Interest to study the creep behaviour

DESOLINATION project

19 industrial and research experts from solar and desalination fields

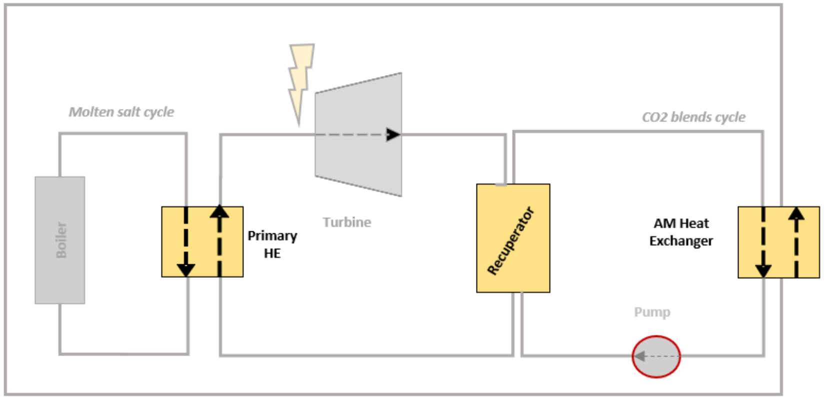
DESOLINATION application case



4 innovative blocks for an optimised CSP and desalination coupling

DESOLINATION HX requirements

Adapted Heat exchangers



CHALLENGES

Specific conditions of temperature and pressure required by:

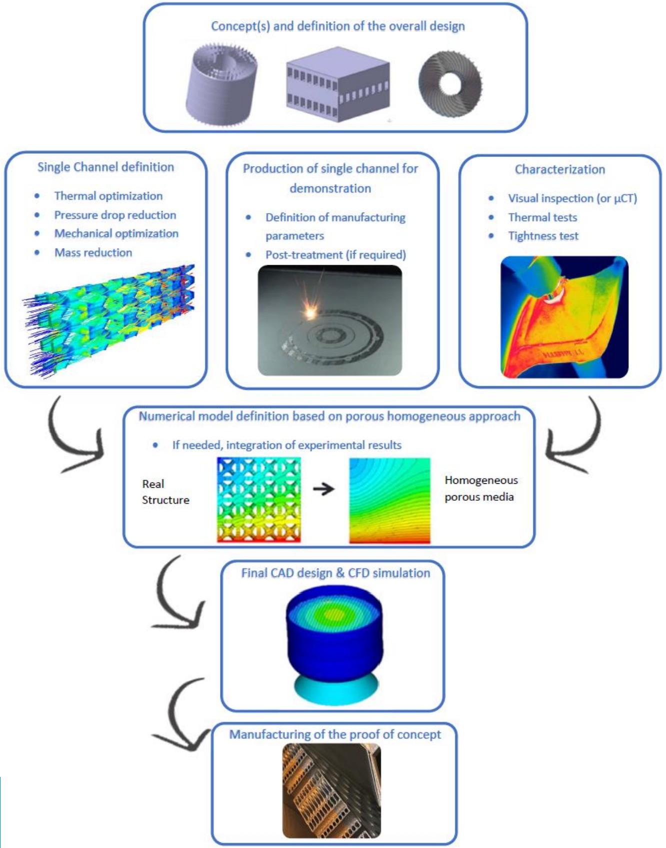
- Primary conditions > 220 bar & 580°C
- Powerblock efficiency > 30%
- sCO_2 blend as working fluid

High stress on the heat exchangers

Innovative heat exchangers adapted to the CSP-desalination system

Primary HX development

Methodology



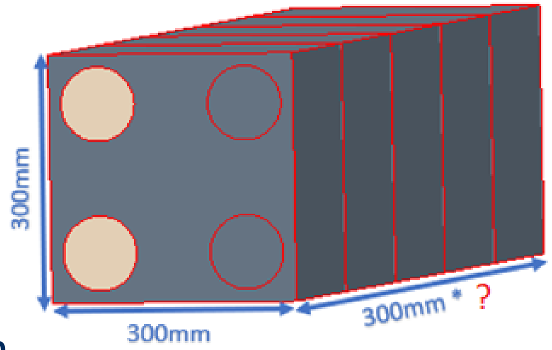
Primary HX development

Concept and design

- Modular approach to minimize the manufacturing risk

→ Definition of parameters

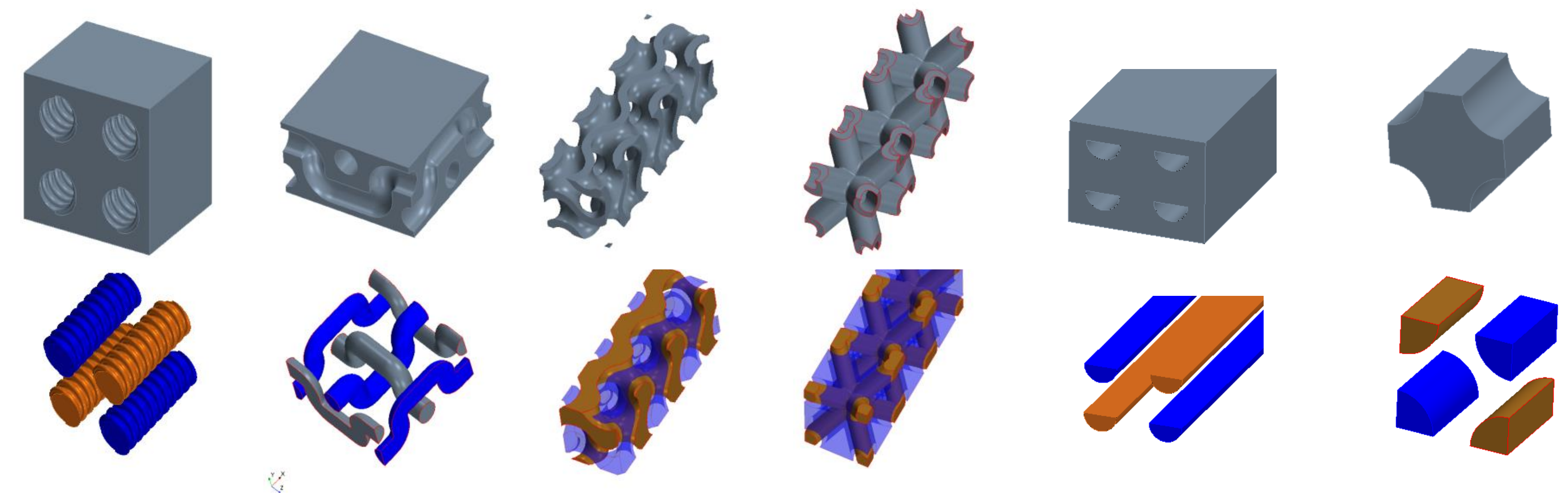
  - Global heat transfer coefficient
  - Heat exchange surface
  - Fluid pressure drop



- Aims: definition of the module number & organisation

Primary HX development

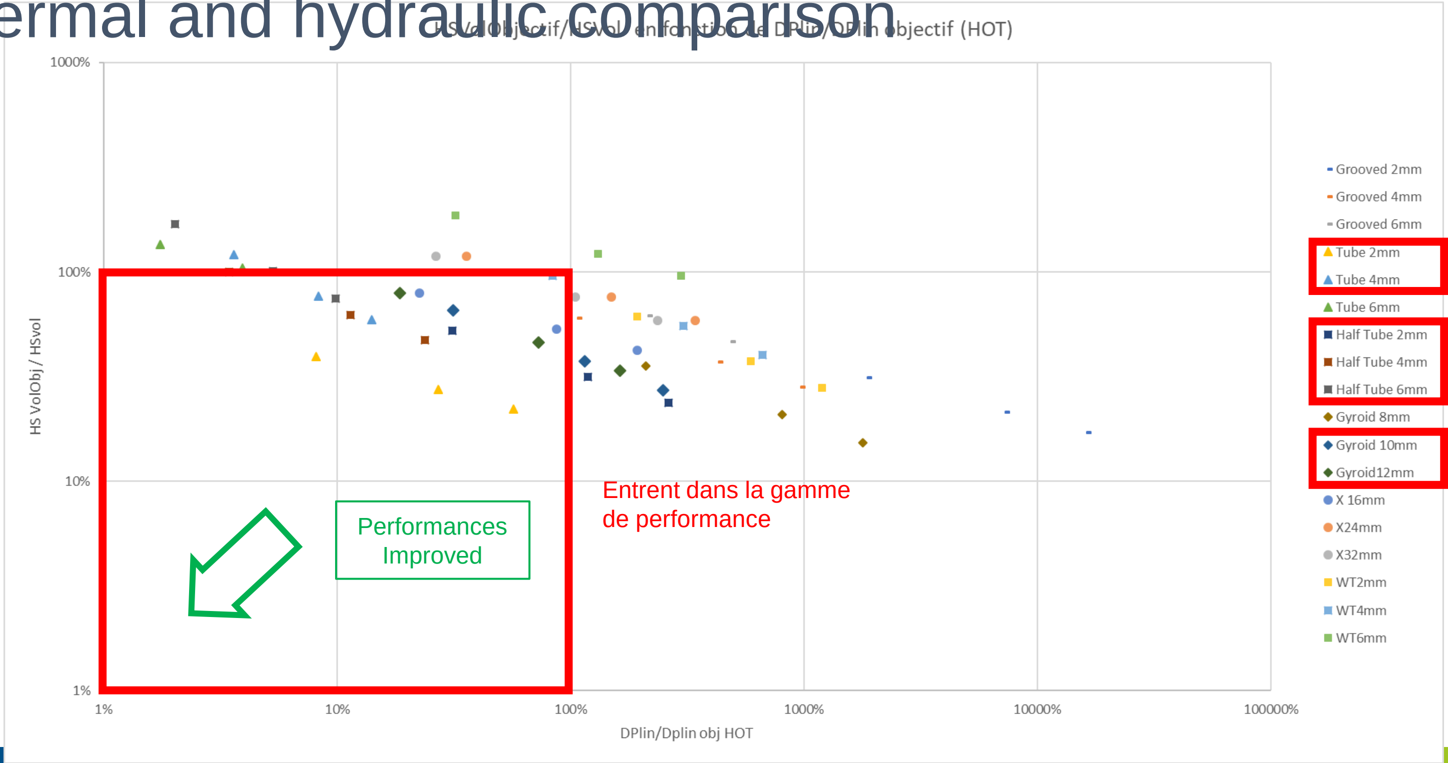
Grooved Tubes | Woven textile | Gyroid | Hollow X lattice | Half Tubes | Full Tubes



Internal Structure

- Front de pareto des solutions présentant le Hsvolumique global en fonction de DP linéique chaud

Thermal and hydraulic comparison

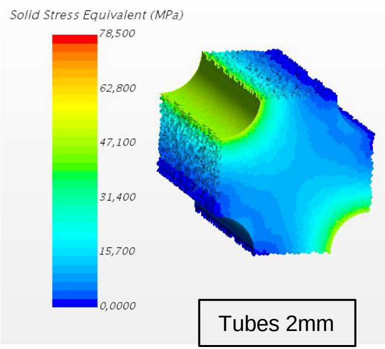


Internal stucture

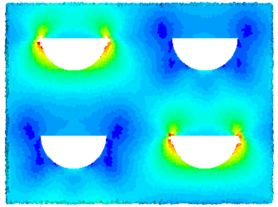
Mechanical comparison: Von Mises criter

Von Mises Max sécurité : 78,5 Mpa

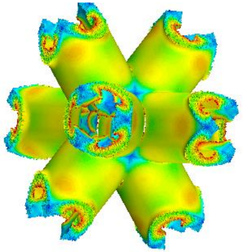
Structure	Von Mises Max / Von Mises Securite
Tube 2mm	63%
Tube 4mm	68%
Gyroid 8mm	76%
Tube 6mm	76%
WT 2mm	89%
Gyroid 12mm	95%
Gyroid 10mm	97%
WT 6mm	99%
WT 4mm	99%
Half Tube 2mm	223%
Xlattice 24mm	298%
Half Tube 4mm	306%
Xlattice 16mm	326%
Xlattice 32mm	378%
Half Tube 6mm	409%



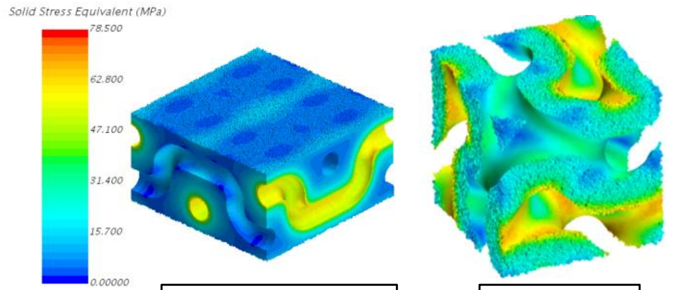
Tubes 2mm



Half Tubes 2mm



Lattices 24mm

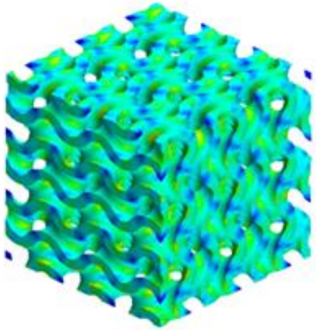


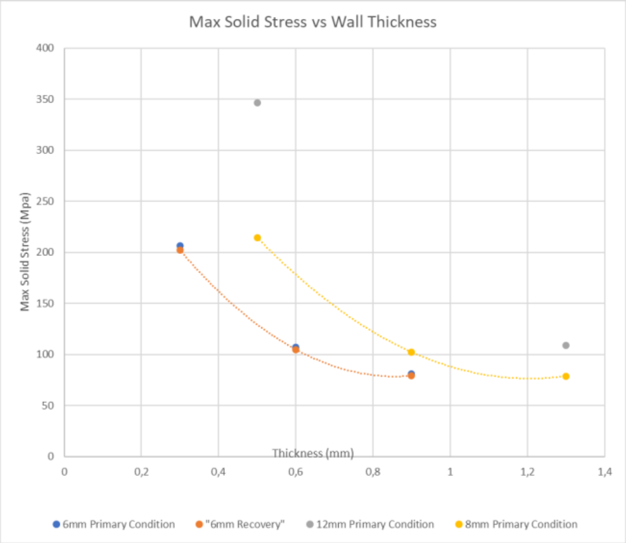
Woven Textile 2mm

Gyroid 8mm

Internal structure

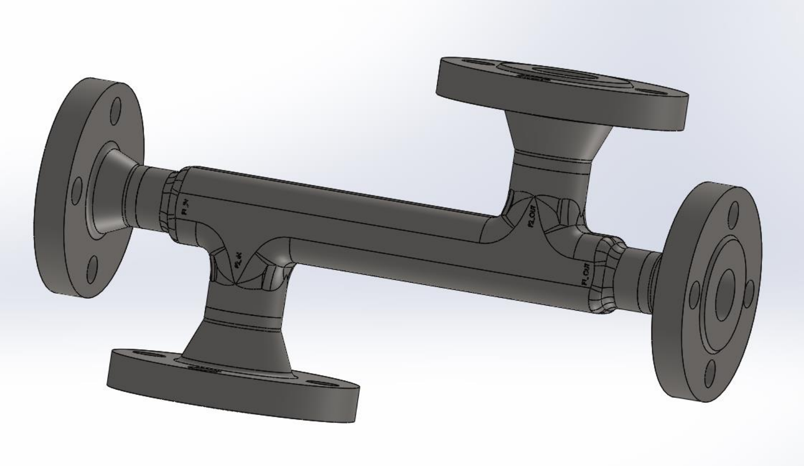
Focus on TPMS structure

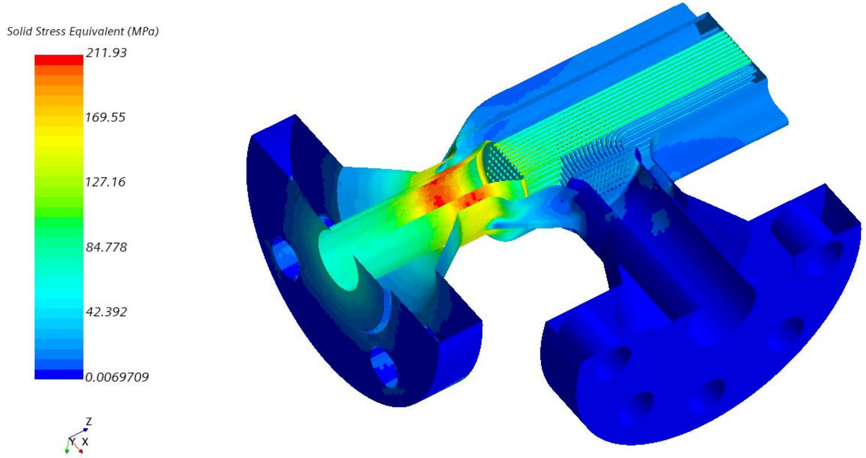




Primary HX development

Mockup development





- To be tested at LUT university test bench

Conclusions

- Additive manufacturing is a promising manufacturing process
  - Improve HX performance
  - Use of new alloys
  - Cost reduction for high value alloys

- DESOLINATION project
  - Mockup are under manufacturing
  - Promising design will be delivered and tested

Acknowledgement

This work is partially funded by the DESOLINATION project

DESOLINATION

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Thank you and see you next time!

Question / comments?

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