sCO2-4-NPP: Innovative sCO2-Based Heat Removal Technology for an Increased Level of Safety of Nuclear Power Plants

Deliverable D4.4

Preliminary design and models of the sCO2-4-NPP heat exchangers

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Type		
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DEM	Demonstrator, pilot, prototype, plan designs	
DEC	Websites, patents filing, press & media actions, videos, etc.	
OTHER	Software, technical diagram, etc.	
Dissemination level		
PU	PUBLIC, fully open, e.g. web	X
CO	CONFIDENTIAL, restricted under conditions set out in Model Grant Agreement	

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Table of contents

List of Tables

List of Figures

1 List of Acronyms

Abbreviation / Acronym	Description / meaning
CHX	Compact Heat eXchanger
DUHS	Diverse Ultimate Heat Sink
FPM	Fins Per Meter
NPP	Nuclear Power Plant
sCO_2	Supercritical CO_2
WP	Work Package

2 Executive Summary

Deliverable D4.4 aims to present the preliminary design and models of the sCO2-4-NPP heat exchangers (heat recovery exchanger CHX and heat sink exchanger DUHS).

These heat exchangers are key equipment in the sCO2-4-NPP safety loop, and their design is needed to complete the cycle design in WP2:

- The main heat recovery heat exchanger transfers heat directly to the sCO2-4-NPP cycle
- The heat sink exchanger transfers remaining heat to the environment.

This deliverable presents the estimated expected performance and size of the components in order to adjust the overall design of the cycle.

A detailed description of the DUHS design is given in this document. The CHX design is not fully presented here to preserve confidentiality, since the design of this heat exchanger is subject to potential patenting, which is still ongoing at the time of submitting this deliverable.

Both heat exchanger models will be integrated in the computer codes in WP2.

The design ideas used to achieve this deliverable will be tested on lab-scale mock-ups to ensure the overall performance of the system and the capability of the heat exchangers to be efficient in steady and transient conditions.

3 Introduction

As part of the sCO2-4-NPP project, a new heat exchanger design is planned based on the heat exchanger designated in the European sCO2-HeRo project.

The first section of this document starts with a detailed description of the followed steps to define and adjust relevant thermodynamic data to heat exchangers design, in accordance with the overall cycle and turbomachinery requirements. The main concern for heat exchangers design is thermal gradients that may lead to fatigue degradation of the materials constituting this equipment and failure, and the feasibility of the design.

The heat exchangers presented in the following sections are designed according to brazed plates and fins heat exchanger technology.

The advantages of this technology are an important heat exchange capability with low pinch and high available flow sections. It also allows meeting the desired thermal duty with low pressure drop leading to a reduction in size and capital cost.

For this project, we also benefit from the knowledge gained from the sCO2-Flex project on design and mechanical resistance of this heat exchangers technology.

The results of the DUHS design are succinctly described in the document.

Several technical details are omitted on the CHX design section to ensure confidentiality of major information which is subjected to a patent filing.

4 Work achieved during the design of heat exchangers components

4.1 Heat exchangers design data

The heat exchangers design presented in the following sections (dimensions, geometry, thermal performances) was achieved using Fives proprietary software, which have proven their reliability over several years of Fives heat exchangers marketing.

4.1.1 First design data

In WP2 of the project, an initial cycle design of a 10MW sCO2-Brayton cycle was conducted. Its purpose is to provide the partners with initial data for component design. For the heat exchangers (CHX /DUHX) Fives Cryo received first design data from USTUTT. These data are summarized in the table below:

Table 1: Initial design data for heat exchangers

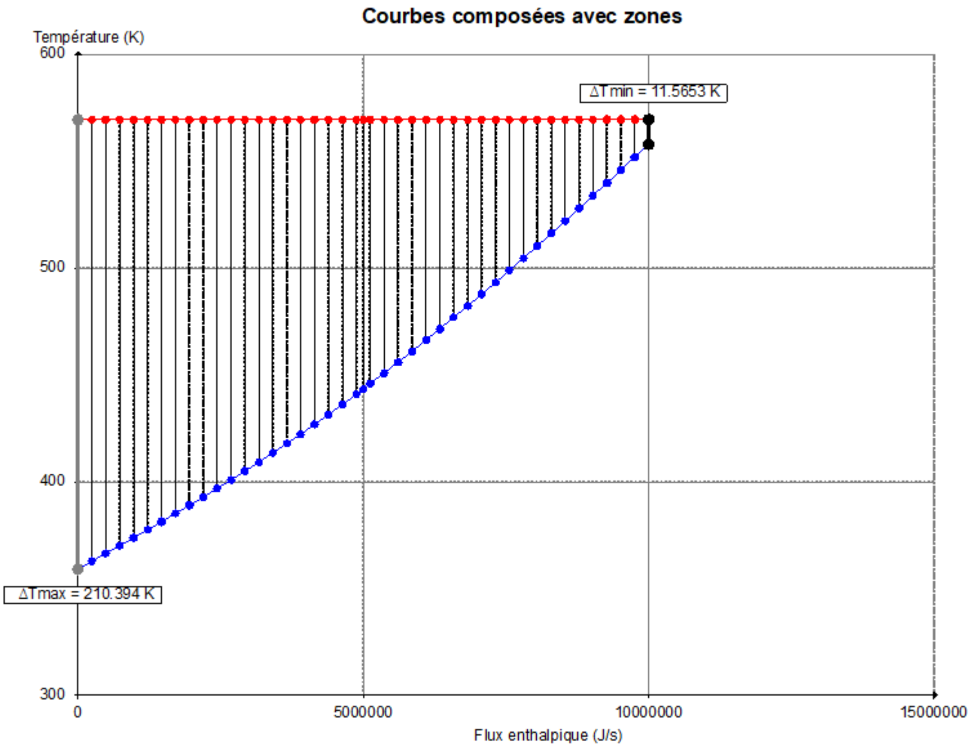
	CHX		DUHS	
	Steam	**sCO2**	**sCO2**	**Air**
P_in (MPa)	8.18	25.61	12.90	0.10
P_out (MPa)	8.16	25.41	12.87	0.10
ΔP (mbar)	**200**	**2000**	**250**	**0**
T_in (°C)	296.56	89.42	228.44	45.00
T_out (°C)	296.39	286.56	55.00	130.00
H_in (kJ/kg)		379.19	656.74	318.59
H_out (kJ/kg)		700.24	347.80	404.49
m (kg/s)	6.99	6.99		116.42
Q (MW)	10.00		9.62	

Table 1 contains design specifications resulting from ATHLET calculations. ATHLET uses very simple models for heat exchangers, in fact one representative channel with a representative heat transferred. This channel is simply multiplied with the number of channels to achieve the total amount of transferred heat, which is required. Local conditions, like pressure drop on the atmospheric side of the DUHS is neglected, because

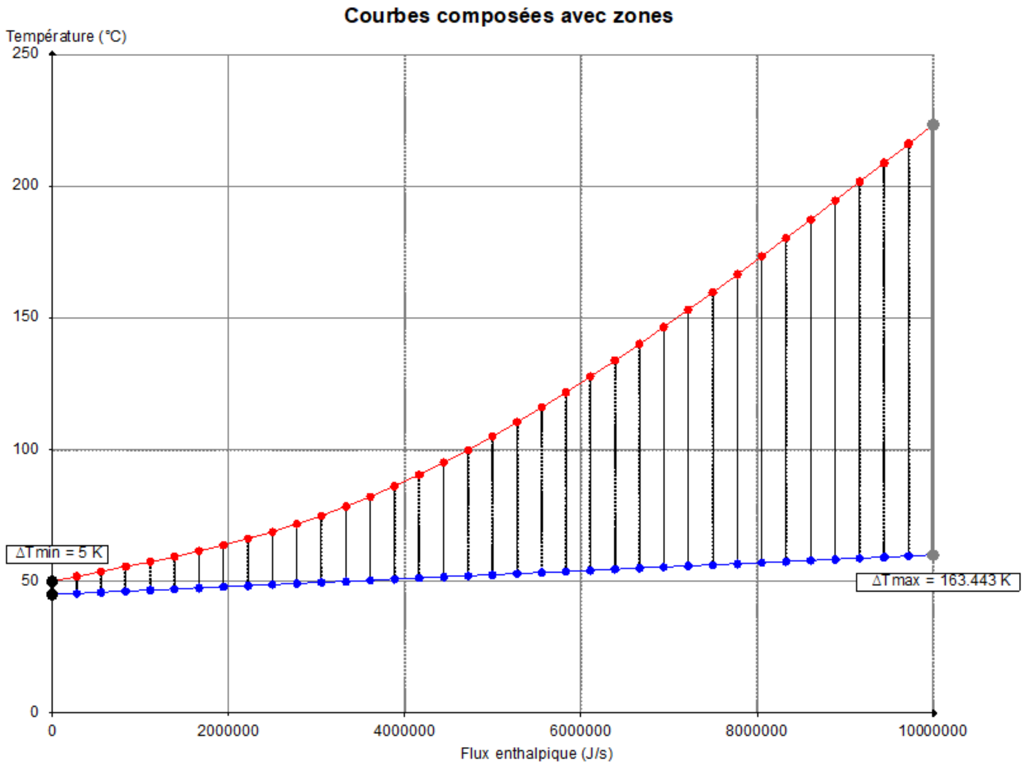
ATHLET assumes that the atmosphere can absorb heat as long as the driving temperature difference is maintained. Thus, the data in Table 1 serve as input data for the mechanical design. The purpose of the mechanical design is to assess the feasibility of the components, propose a first layout and reflect improved data (Table 2) to the code users, who – in turn – will improve their simplified models to meet the new data.

Some of these data needed to be optimized, such as the pressure drop values: for example, it is unlikely to design a DUHS heat exchanger considering no pressure drop at all on air side. The optimization of these data was achieved during the project and the design of components presented in the following sections is based on these optimized data.

Fives Cryo used these preliminary input data to calculate enthalpy curves for both DUHS and CHX as shown in Figure 1.



CHX : ΔT max = 210°C



DUHS: ΔTmax=163°C

Figure 1: Enthalpy curves for CHX and DUHS

Since the actual appropriate material to manufacture brazed stainless steel plates and fins heat exchangers is 316 grade stainless steel, the maximum temperature difference in the DUHS should be reduced to 100°C in order to meet with the material characteristics.

This was possible for DUHS; USTUTT managed to modify and provide us with new input data meeting these requirements, but it is not the case for CHX. For CHX, a more appropriate solution is to consider a nickel-based alloy, which will withstand such high thermal gradients. This type of material is widely used in nuclear power plants and reference systems such as RCC-M will enable us to check that the material chosen meets the expectations of nuclear standards.

4.1.2 Adjusted design data

Several discussions were held within WP4 to define the set of thermodynamic input data for heat exchangers design and to adjust it according to heat exchangers manufacturing feasibility and the overall requirements for the other components of the cycle.

Table 2 summarizes the adjusted data used for DUHS and CHX design. In red, the modified data, which allow us to reduce as much as possible the maximum temperature differences for both heat exchangers, and to authorize minimal pressure drops on air side.

For CHX, CO_2 inlet and outlet pressures were reduced respectively down to 21.42 MPa and 21.22 MPa, keeping the same pressure drops. CO_2 inlet temperature was also reduced to 80.84°C, along with inlet enthalpy which was also slightly reduced to 372.14 kJ/kg. Outlet enthalpy was slightly increased to 708.30 kJ/kg. For steam side, inlet temperature was increased to 308°C and outlet temperature was decreased to 150°C, which helped to reduce efficiently the thermal gradient between inlet CO_2 and outlet steam (fluids circulate in counter-flow). The steam flow rate was reduced to 4.59 kg/s.

For DUHS, CO_2 inlet and outlet pressures were slightly modified to 12.70 MPa and 12.68 MPa respectively, reducing the pressure drop down to 200 mbar. Inlet temperature was increased to 243.19°C along with an increase of the inlet enthalpy to 674.88 kJ/kg. The outlet enthalpy was slightly modified to 350.97 kJ/kg. For air side, inlet pressure was slightly increased to allow a consideration of minor pressure drops of 3 mbar instead of 0 mbar initially. The outlet temperature was decreased to 115.21°C and outlet enthalpy slightly lowered to 389.50 kJ/kg. Air mass flow rate was increased to 135.87 kg/s. CO_2 mass flow rate in the cycle was increased to 29.74 kg/s.

Table 2: Thermodynamic input data used for DUHS and CHX design

	CHX		DUHS	
	Steam	**sCO2**	**sCO2**	**Air**
P_in (MPa)	8.18	21.42	12.70	0.1003
P_out (MPa)	8.16	21.22	12.68	0.10
ΔP (mbar)	**200**	**2000**	**200**	**3**
T_in (°C)	308.00	80.84	243.19	45.00
T_out (°C)	150.00	286.57	55.00	115.21
H_in (kJ/kg)		372.14	674.88	318.59
H_out (kJ/kg)		708.30	350.97	389.50
m (kg/s)	4.59	29.74		135.87
Q (MW)	10.00		9.63	

The heat exchangers presented in the following sections are designed according to brazed plates and fins heat exchanger technology.

The advantages of this technology are an important heat exchange capability with low pinch and high available flow sections. It also allows meeting the desired thermal duty with low pressure drop leading to a reduction in size and capital cost.

4.2 DUHS design

Thanks to the efforts made on the thermodynamic design input data, we were able to design the DUHS in 316 grade stainless steel, which is a more economical solution in comparison to nickel-based alloys (well known for withstanding high thermal gradients), and also compatible with the regulations to be applied for this type of equipment.

The design data in Table 3 were considered as close as possible to the thermodynamic data for the overall cycle in the previous table.

Table 3: DUHS design data

FLUID		CO2	AIR
TOTAL FLOWRATE	kg/s	30.49	132.49
OPERATING PRESSURE	MPa a	11.92	0.1
ALLOWABLE PRESSURE DROP	kPa	25	0
TEMPERATURE IN	°C	238.66	45
TEMPERATURE OUT	°C	55	115.22
SPECIFIED HEAT TRANSFERRED	MW	9.419	9.419
CORRECTED MTD (GLOBAL)	°C	23.693	

The design was achieved using proprietary software of Fives Cryo. The calculated output data are shown in Table 4. Calculated pressure drops are considered at nominal flow rate x1.

Table 4: Calculated output

FLUID		CO2	AIR
CALCULATED PRESSURE DROP	kPa	8	0
DESIGN TEMPERATURE	°C	-30 °C / 300 °C	
DESIGN PRESSURE	MPa g	23	1
HYDRAULIC TEST PRESSURE	MPa g	29.9	1.3

The design leads to 20 heat exchanger cores for each unit, each core has the following dimensions:

- Width: 2000 mm
- Height: 987 mm
- Length: 570 mm

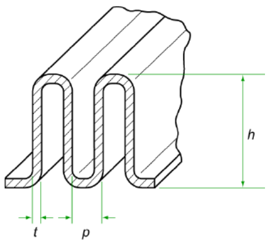
For a total number of 120 cores for all 6 units.
Each core is a counter-flow heat exchanger with a total number of layers of 196 per core.

The layers are distributed as follows:

- 64 layers for CO_2
- 128 layers for air
- 4 "dummy" layers, which are inactive layers, 2 on bottom stacking and 2 on top, to guarantee the mechanical integrity of the heat exchanger cores.

The material for DUHS core construction is 316 Ti stainless steel (UNS number S31635 / W. number 1.4571). This alloy is suitable for brazing-diffusion bonding and it can withstand high temperature and high temperature differences between fluids. It also benefits from a high mechanical strength and corrosion/erosion resistance. Each layer has a height of 4 mm. Both CO_2 and air layers contain “plain” fins but with different geometries, as shown in Table 5.

Table 5: DUHS geometry of fins

	CO_2 side fins	Air side fins
Thickness t (mm)	0.3	0.15
Height h (mm)	4	4
FPM p (Fins Per meter)	787.4	393.7
Geometry of “plain fins”		

The parting sheets between DUHS core layers are 1 mm thick, external sheets are 4 mm thick.

The thermal performance of our DUHS design is achieved thanks to a smart design: in fact, the stacking pattern used is called “double-banking”, leading to an arrangement of 2 air layers against 1 CO_2 layer alternatively. Also, for the CO_2 side, each layer is constituted of 6 passes as shown in Figure 2, which allow connecting the headers and nipples on only one side of each heat exchanger core (see Figure 3), which is quite practical in order to gain space on the unit.

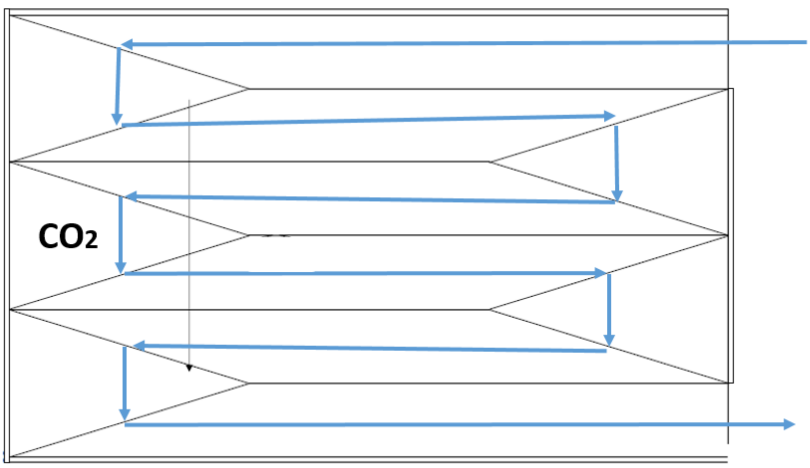


Figure 2: DUHS CO_2 layer sketch constituted of 6 passes

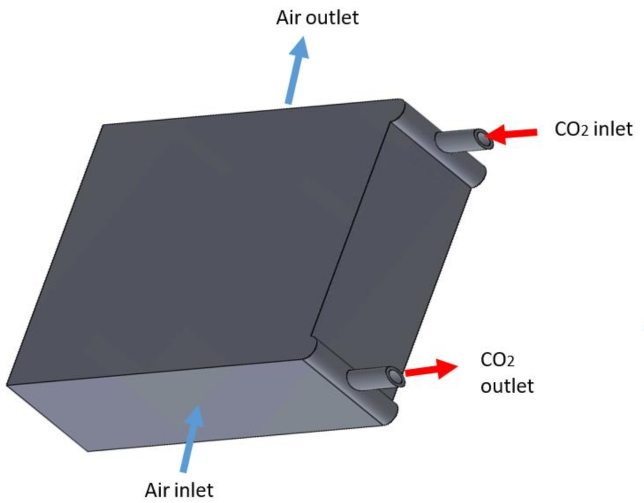


Figure 3: Overall DUHS sketch

Therefore, there are no headers intended for air side, since we consider a circulation through the whole width perpendicularly, with subtracting obviously the lateral bars width, as shown in Figure 4, which corresponds to an effective passage width of 1928 mm.

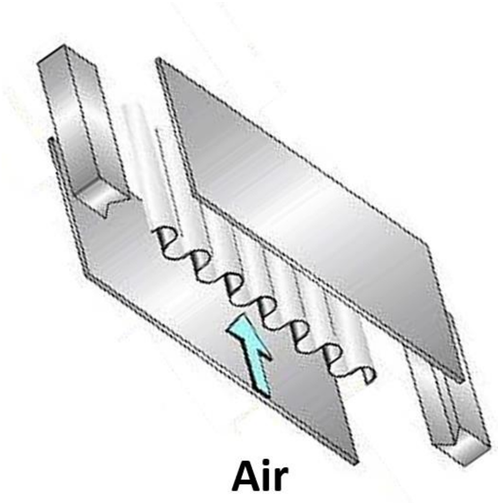


Figure 4: DUHS Air circulation sketch

The output design data are summarized in Table 6. This DUHS design allows to develop a total heat transfer area of 9376 m² for CO_2 and 13581 m² for air for 1 unit of 10 MW.

Table 6: DUHS output design data

FLUID		CO2		AIR	
EFFECTIVE PASSAGE WIDTH	mm	83		1928	
EFFECTIVE PASSAGE LENGTH	mm	12000		560	
TOTAL HEAT TRANSFER AREA	m2	9376		13581	
TOTAL FREE FLOW AREA	cm2	3002		178802	
NOZZLE SIZE (NOMINAL) IN/OUT	mm	2x40	2x40		
CONNECTIONS (NOM.) IN/OUT	inch	40 x 1.5	40 x 1.5		

4.3 CHX design

The input thermodynamic data for CHX design in Table 2 were used to generate secondary input data in order to match a new design idea, allowing to reduce optimally thermal gradients between fluids.

This design idea is currently under assessment for patent submission, jointly between Fives, USTUTT and KSG/GFS.

Therefore, several design details will be omitted from this deliverable to guarantee confidentiality of this work while patenting procedure is still ongoing.

The CHX design was achieved to lead specifically to only one very compact heat exchanger. In fact, the discussions with the project partners on CHX specifications led NRI and CVR to specify the position and shape on this heat exchanger: it should be in flat design, to allow placement on the available wall of the room number A820 as shown in Figure 5.

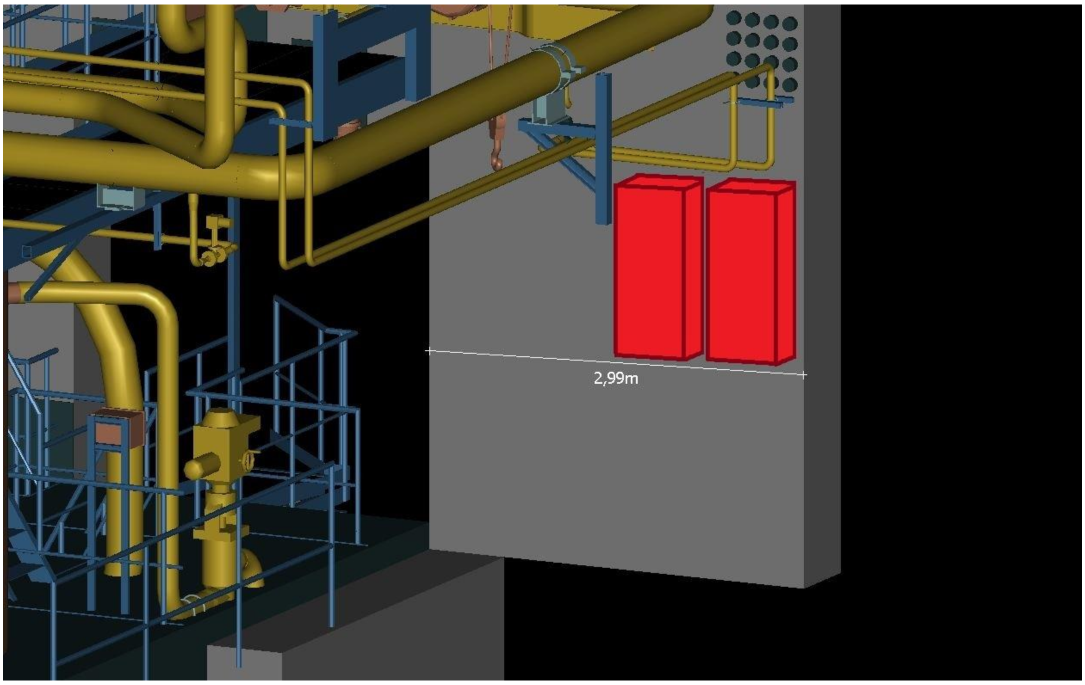


Figure 5: Room A820, layout of heat exchangers steam/sCO_2

The depth (B) should be less than 30 or 40 cm and height (H) should be around 1,5 m (see Figure 6).

The exchanger height is limited at the top by the wall penetration, and the bottom of the heat exchanger should be higher than minimal level for maintaining the minimal slope of the pipeline of condensed water.

The length of the exchanger is limited only by length of the wall (2,99 m).

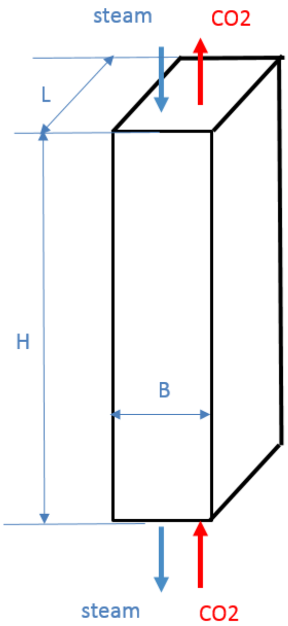


Figure 6: CHX position and shape sketch

The design achieved by Fives, taking account of the specifications listed before, led to a single core with the following dimensions:

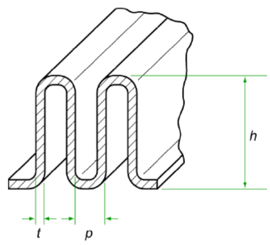
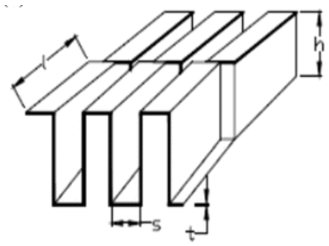
- Width: 700 mm
- Height: 512 mm
- Length: 2000 mm

It is a counter-flow heat exchanger with a total number of layers of 101. The layers are distributed as follows:

- 38 layers for CO_2
- 59 layers for steam
- 4 “dummy” layers, which are inactive layers, 2 on bottom stacking and 2 on top, to guarantee the mechanical integrity of the heat exchanger cores.

Each layer has a height of 4 mm. Both CO_2 and air layers contain “plain” fins but with different geometries, as shown in Table 7.

Table 7: CHX geometry of fins

	CO_2 side fins		Steam side fins	
	Distributors	Exchange	Distributors	Exchange
Thickness t (mm)	0.3		0.3	0.15
Type	Plain		Plain	Serrated
Height h (mm)	4			
FPM p (Fins Per meter)	787.4		393.7	629.9
Fins geometry sketch				

The parting sheets between CHX core layers are 1 mm thick, external sheets are 4 mm thick.
This CHX design allows to develop a total heat transfer area of 305 m² for CO_2 and 278 m² for a 10MW unit.

5 Conclusion

Important work has been achieved on defining clearly the input thermodynamic data to allow the design of the components of the sCO2-4-NPP cycle, amongst them, the heat exchangers CHX and DUHS.

Thanks to proprietary software of Fives, the design of these heat exchangers was completed and gives essential information to be used in the computer codes of WP2. The expected performance was assessed according to heat transfer efficiency required, pressure drops and size following the constraints identified for installation locations of this equipment.

These design results will also constitute input data for the establishment of heat exchangers qualification procedures according to nuclear requirements.

The detailed design results for DUHS were fully presented in this document. For CHX, technical data were omitted to ensure confidentiality since this heat exchanger design is subject to a potential patent filing and the procedure is still ongoing.

The conditions for operation of the sCO2-4-NPP loop make it easy to exceed thermal gradients for which the heat exchangers are designed. It is important to define the next step, in the frame of the optimisation of this equipment, as calculations check to establish a performance map on transient phases (start-ups and shut-downs) and on stand-by when the loop is off.