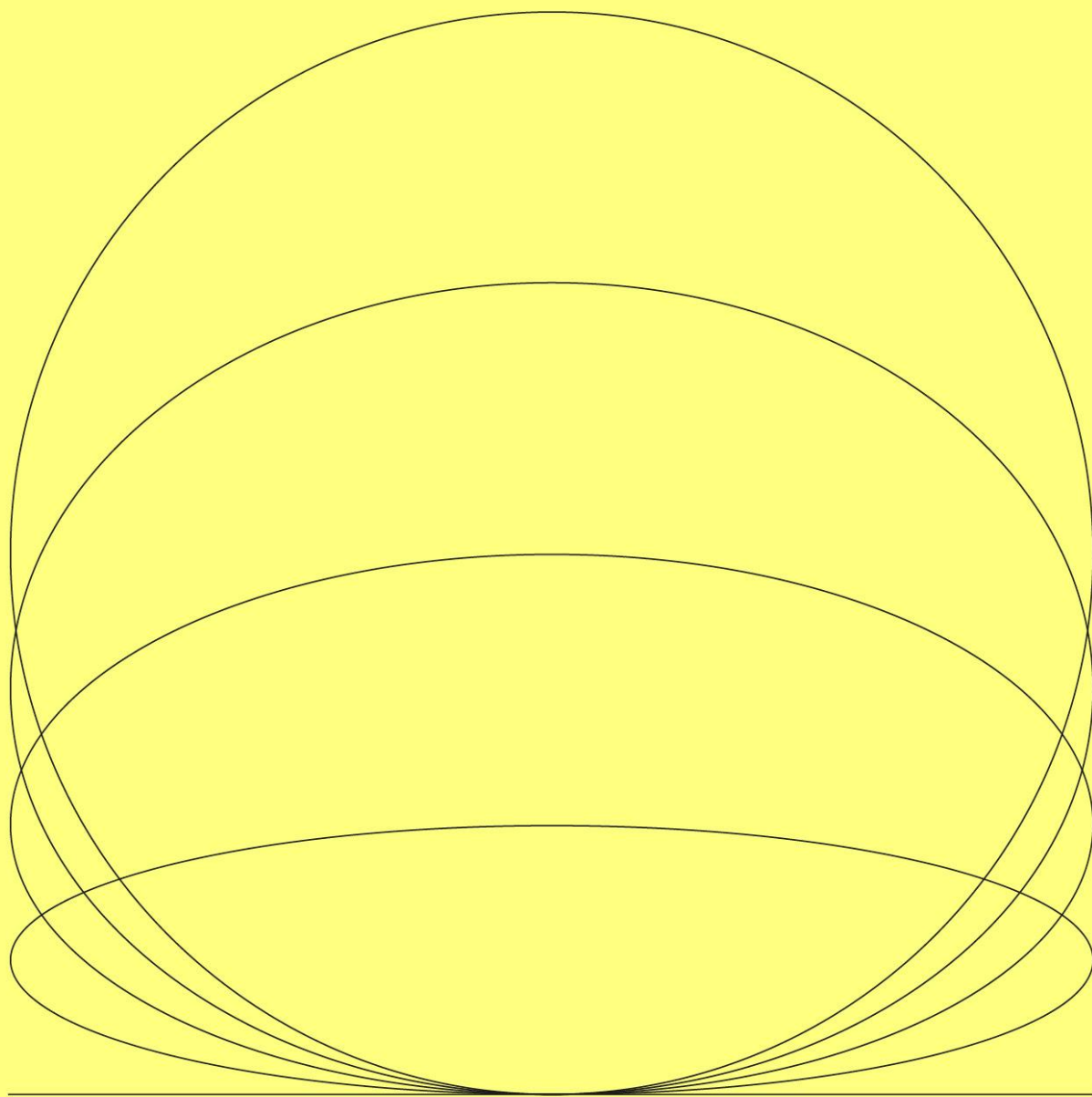




Report

H₂UpScale

Deliverable 7.1

Simulation report

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H₂UpScale



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Acronyms

BoP – Balance of Plant

FC – Fuel Cell

PEMFC – Proton exchange membrane fuel cell

HEX – Heat Exchanger

WP7 – Work Package 7

HT – High-Temperature

MT – Medium-Temperature

ACHE – Air Cooled Heat Exchanger

FEM – Finite Element Method

CFD – Computational Fluid Dynamics

CHT – Conjugate Heat Transfer

TPMS – Triply Periodic Minimal Surface

LPBF – Laser Powder Bed Fusion



Summary

This report summarizes the activities carried out within Task 7.1 towards the design of a 3D-printed heat exchanger for PEMFC thermal energy dissipation in high-power fuel cell systems. Building upon the application-specific requirements defined in D2.1, the fuel cell system requirements established in D2.2, and the thermal system design developed in D3.4, the main objective is to develop an optimized heat exchanger concept suitable for additive manufacturing. The work started with the definition of the design requirements and thermal boundary conditions for the different H2UPSCALE applications, followed by the selection of the most suitable material considering thermal performance, structural integrity, and LPBF manufacturing requirements. In parallel, the relationship between LPBF process parameters and the resulting surface roughness was assessed due to its direct impact on heat transfer performance. Different heat exchanger concepts were then developed, evaluated through CFD simulations, and optimized for additive manufacturing, resulting in a scalable thermal management solution for the high-power applications targeted within the H2UPSCALE project.



1. Definition of system requirements for the design - T7.1.1

The H2UPSCALE system architecture is based on three power nodes that scale a common 175 kW PEM fuel cell stack and Balance of Plant (BoP) across different transport sectors. Node 1 targets heavy-duty road applications with 350 kW net power (2 stacks), Node 2 addresses medium-power maritime applications with 700 kW (4 stacks), and Node 3 covers high-power maritime and aviation applications with 1050 kW (6 stacks). This modular approach maximizes component commonality, scalability, and cost reduction across all use cases.

Based on this architecture, the thermal management requirements associated with each node must be identified and quantified in order to support the design of the heat exchanger system. The different power levels and operating conditions of the three nodes lead to distinct heat rejection demands, which constitute the basis for the sizing and optimization of the thermal dissipation system.

The design requirements for the different H2UPSCALE applications are summarized in the following table. The design inputs have been classified into four categories: Application and Type, Operating Conditions, Performance Targets, and Design Constraints, including the available installation volume. In addition, the thermal system architecture defined in WP3 highlights the need for two dedicated heat exchangers within each node: a High-Temperature (HT) heat exchanger and a Medium-Temperature (MT) heat exchanger.

These heat exchangers are required to satisfy the thermal dissipation requirements associated with the respective system circuits and their operating conditions. The parameters presented in the following table provide the basis for the sizing and optimization of both heat exchanger systems.

1.1. Design requirements Node 1

Table 1. Design requirements

Design Inputs Node 1				Middle Temp HEX	High Temp HEX
1	Application and type	1.1	Application	Heavy Duty truck PEMFC	
		1.2	HEX type	Air cooled (ACHE)	
2	Operating Conditions	2.2	Max Air Temp	40 °C	
		2.3	Air Flow rate	12 kg/s	
		2.5	Coolant Temp In	65 °C	88 °C
		2.6	Coolant Flow rate	75 L/min	420 L/min
3	Performance Targets	3.1	Hydraulic Losses	<25 kPa	<40 kPa
		3.2	Thermal Power	45 kW	380 kW
4	Design Restraints	4.1	Design Volume	Total thickness 160mm	



The values defined for Node 1 were selected as the basis for the heat exchanger development and are subsequently used to extrapolate the requirements of Nodes 2 and 3. Since the H2UPSCALE thermal management architecture follows a modular approach, the same MT and HT heat exchanger designs can be replicated to satisfy the increased thermal demands of the higher-power nodes. Accordingly:

Node 1: 1 MT HEX + 1 HT HEX

Node 2: 2 MT HEX + 2 HT HEX

Node 3: 3 MT HEX + 3 HT HEX

Assuming that the HEXs can be installed as independent units without significant aerodynamic interaction between them, each module maintains the same heat rejection capability and hydraulic performance targets defined for Node 1. Under these conditions, the thermal management requirements of the different PEMFC systems can be fulfilled through a scalable and modular architecture, while preserving the validated performance of the individual heat exchanger design.

Consequently, the design requirements defined for the Node 1 HEX are considered representative of the modular thermal management concept proposed within H2UPSCALE and therefore establish the baseline specifications for the heat exchanger development process.

Based on these requirements, the next stage focuses on the selection of the most suitable material for the heat exchanger. Particular attention is given to compatibility with LPBF processing and to the impact of manufacturing-related characteristics on thermal performance. The outcome of this assessment establishes the material and manufacturing framework that will guide the subsequent heat exchanger design, simulation, and optimization activities.

2. Selection of the optimal material - T7.1.2

The material selection for the Laser Powder Bed Fusion (L-PBF) manufacturing of the heat exchanger (HeX) was carried out considering the functional requirements of the component, achievable material properties, LPBF processability, and compatibility with the coolant.

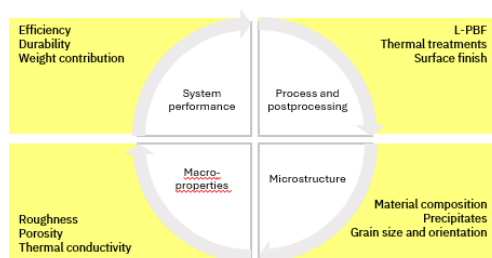
In a first step, an initial material screening was performed considering different metallic material families with potential for this application. AlSi10Mg, AlSi7Mg, CuCrZr, commercially pure copper (CP Cu), CuNi30, and SS316L were considered, covering a wide range of properties and thermal conductivities.

Initial materials selection based on:

- HeX requirements
- Achievable material properties
- Processability by L-PBF
- Compatibility with coolant

Material	Thermal conductivity (W/mK)
AlSi10Mg	130-190
AlSi7Mg	150-180
CuCrZr	320-360
CPCu (commercially pure Cu)	391-401
CuNi30	29-35
SS 316 L	16

Iterative design of experiments for AM part optimization with 4 levels:



- i. Material final selection
- ii. Process parameter screening
- iii. Geometrical feature-based
- iv. Application-based

Figure 1. Materials and main criteria considered during the initial screening for the L-PBF manufacturing of the HeX.

Thermal conductivity was considered one of the main selection criteria due to its direct influence on the heat dissipation capacity of the HeX. Copper alloys provide the highest thermal conductivity, while aluminum alloys offer a good balance between thermal conductivity, low density, and L-PBF processability. On the other hand, SS316L has significantly lower thermal conductivity but provides high corrosion resistance and well-established L-PBF processability.

To facilitate the presentation of the experimental results and preserve confidentiality regarding the material screening and selection process, the candidate materials evaluated in this study are identified throughout this deliverable as Material 1, Material 2, Material 3, and Material 4. These designations are used consistently in the experimental, corrosion, and manufacturing assessments presented in the following sections

Based on this first analysis, Materials 1, 2, and 3 were selected as candidate materials for further experimental evaluation. These materials were chosen to represent different approaches to the heat exchanger requirements and to experimentally assess the balance between thermal performance, corrosion behaviour, density, and LPBF processability.

The three selected materials were then processed by LPBF to verify their manufacturing feasibility and to produce the samples required for the following experimental activities.



Figure 2. LPBF manufactured geometries corresponding to the selected candidate materials

Since the HeX material will be in direct contact with the coolant during operation, its corrosion behaviour was considered as an additional criterion in the material selection process. For this reason, corrosion tests were performed on Material 1, 2, and 3 using different coolant formulations developed within the project.

In this section, only the main corrosion results relevant to the material selection are presented. The complete corrosion testing procedure, test conditions, and detailed results for the evaluated materials will be described in deliverable 7.3.

The tests showed different behaviours for the three materials. Material 1 showed good behaviour, with no relevant signs of corrosion under the evaluated conditions. Material 2 showed an overall favourable behaviour, although slight signs of corrosion were observed, while Material 3 showed evidence of corrosion.

Table 2: Summary of corrosion behaviour of the three evaluated candidate materials.

Material	Observed corrosion behaviour
Material 1	Good
Material 2	Slight corrosion / favourable behaviour
Material 3	Corrosion

The results showed a trade-off between thermal conductivity and corrosion behaviour. Material 3 provides the highest thermal potential but showed the least favourable behaviour with the coolant. In contrast, Material 1 showed good stability, although its low thermal conductivity limits its potential to maximise heat transfer. Material 2 showed an intermediate solution, combining significantly higher thermal conductivity than Material 1 with relatively favourable corrosion behaviour.

Based on these results, the search was extended to alternative materials able to provide a suitable balance between high thermal conductivity, LPBF processability, and corrosion behaviour. In this context, Material 4 was identified as a material of particular interest for the application.

Material 4 is specifically developed for additive manufacturing by LPBF. The material presents interesting properties for thermal management applications, combining high thermal conductivity, low density, and good LPBF processability.

To experimentally evaluate its potential within the project, Material 4 powder was acquired to develop an initial LPBF manufacturing condition and to produce new samples for corrosion testing.

Although Material 4 is specifically developed for LPBF, it is a relatively new alloy, and the manufacturer of the LPBF equipment available at the technological centre does not yet provide a developed and optimised material profile specifically for Material 4. For this reason, an initial processing condition had to be developed to obtain consolidated material and manufacture the samples required for its evaluation.

The available Material 2 profile was used as a starting point for the configuration of the new Material 4 profile, while the main bulk parameters were defined using processing conditions published specifically for Material 4 as a reference. The first manufacturing strategy was focused on obtaining good material consolidation, without developing specific edge or contour parameters at this stage. Therefore, surface roughness optimisation was not the objective of this initial step. The objective was to obtain a stable manufacturing condition that allowed the samples to be successfully produced.

The initial bulk condition is summarised in table 3.

Table 3. Initial parameters used for the LPBF manufacturing of Material 4.

Parameter	Value
Layer thickness	60 µm
Hatch power	370 W
Hatch distance	0.13 mm
Hatch point distance	28 µm
Exposure time	20 µs

The selected parameters are consistent with published processing conditions for material 4. For a 60 µm layer thickness, reference conditions of 370 W laser power, 0.13 mm hatch distance, and 1400 mm/s scan speed have been reported.

In the L-PBF equipment used, the exposure strategy is defined by the combination of point distance and exposure time. A point distance of 28 µm and an exposure time of 20 µs provide an equivalent nominal exposure speed of approximately 1400 mm/s:

$v = 28 \mu\text{m} / 20 \mu\text{s} = 1400 \text{ mm/s}$

Therefore, the implemented bulk parameters are consistent with the published processing conditions for Material 4, adapted to the specific exposure strategy of the LPBF equipment available at the technological centre.

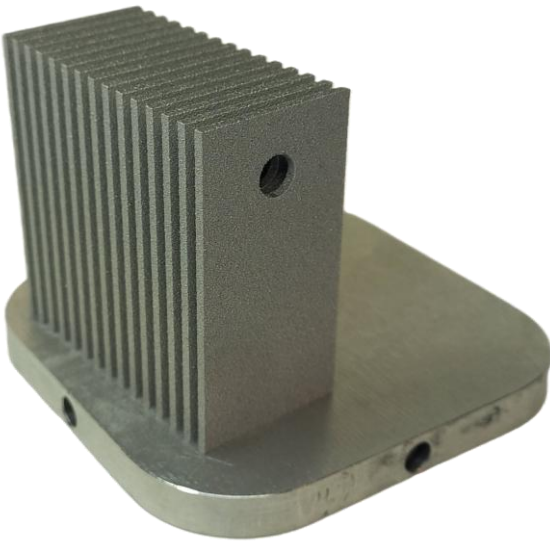


Figure 3. Development of the initial LPBF manufacturing condition for Material 4 and geometry obtained using the selected bulk parameters.

The defined condition provided good manufacturing results, with no relevant problems observed during the process, and allowed the samples required for the material evaluation to be successfully produced.

The Material 4 samples were then subjected to corrosion tests using the selected coolant formulations. Under the evaluated conditions, the samples showed very small mass changes and no signs of moderate corrosion were observed, indicating favourable behaviour in contact with the coolant.

Table 4. Summary of the corrosion test results obtained for material 4.

Material	Observed corrosion behaviour
Material 4	Very good. No signs of significant corrosion

The experimental results showed that Material 4 could be successfully processed by LPBF and presented favourable corrosion behaviour under the evaluated coolant conditions. Considering these results together with its thermal properties, low density, and LPBF processability, Material 4 was selected as the material for the further development of the HeX.

The first manufacturing condition developed for Material 4 was mainly focused on bulk material consolidation, without specific edge parameters to control the surface finish. Therefore, after the final material selection, the next step focused on studying how LPBF manufacturing parameters and strategies can be used to control and improve the surface roughness of Material 4.

This work provides the starting point for Section 7.1.4, where the relationship between LPBF parameters and the surface roughness of Material 4 is experimentally studied through the manufacturing and characterization of geometries representative of the HEX surfaces.

3. HEX design and simulations - T7.1.3

3.1 Design targets

Prior to the heat exchanger design activities, a set of performance targets must be established to define the expected functionality of the component and to provide quantitative criteria for design validation. These targets constitute the key requirements that the proposed design must satisfy and will subsequently be verified through Computational Fluid Dynamics (CFD) simulations, specifically Conjugate Heat Transfer (CHT) analyses. A general effectiveness target has been established for all heat exchanger configurations. In addition, specific thermal and hydraulic performance objectives have been defined for both the Medium-Temperature (MT) and High-Temperature (HT) circuits, based on the system requirements identified in the previous sections.

Hydraulic performance

MT heat exchanger: $\Delta P \leq 25$ kPa

HT heat exchanger: $\Delta P \leq 40$ kPa

Thermal performance

MT heat exchanger: Heat rejection ≥ 45 kW

HT heat exchanger: Heat rejection ≥ 380 kW

These targets constitute the main design criteria used during concept development, CFD evaluation, and subsequent optimization of the HEX geometry for additive manufacturing.

3.2 Design Modeling

The heat exchanger design was developed following the modular philosophy adopted throughout the H2UPSCALE project. Instead of designing a single large heat exchanger adapted to each application, the concept is based on standardized thermal modules that can be combined to satisfy the cooling requirements of the different power nodes while maintaining common interfaces and manufacturing processes.

Each heat exchanger module consists of a cylindrical body containing an internal heat transfer core specifically developed for additive manufacturing. The internal architecture combines flow channels and lattice-based structures derived from Triply Periodic Minimal Surface (TPMS) geometries, providing a highly compact heat transfer solution with an increased surface-area-to-volume ratio. The same module design has been adopted for both the MT and HT circuits, simplifying design, manufacturing, assembly, maintenance, and spare part management while maintaining the modular philosophy of the project.

As a summary, a single module consists of a cylindrical body with a length of 800 mm. Based on this modular configuration, the present report will determine the number of modules required to consolidate one MT heat exchanger (HEX MT) and one HT heat exchanger (HEX HT), establishing the corresponding modular arrangement for each application.

The modular concept enables the heat exchanger system to be configured according to the thermal requirements of each application. Individual modules are manufactured as independent components and subsequently installed and connected within the corresponding cooling circuit. Depending on the required heat rejection capacity, multiple modules can be arranged in parallel to increase the overall thermal performance of the system. This architecture provides several advantages from both operational and maintenance perspectives. In the event of damage or performance degradation, a single module can be replaced without affecting the remaining units, reducing maintenance costs and downtime. Furthermore, the thermal capacity of the system can be easily adapted to different

operating conditions by adding or removing modules without requiring a redesign of the complete heat exchanger assembly.

The resulting concept therefore combines scalability, maintainability, and manufacturing flexibility, while remaining fully aligned with the modular system architecture defined within the H2UPSCALE project. Based on the thermal and hydraulic performance obtained from the CFD and CHT simulations, the number of modules required for each circuit and their corresponding interconnection strategy, including series and parallel arrangements, will be defined to ensure compliance with the MT and HT system requirements.

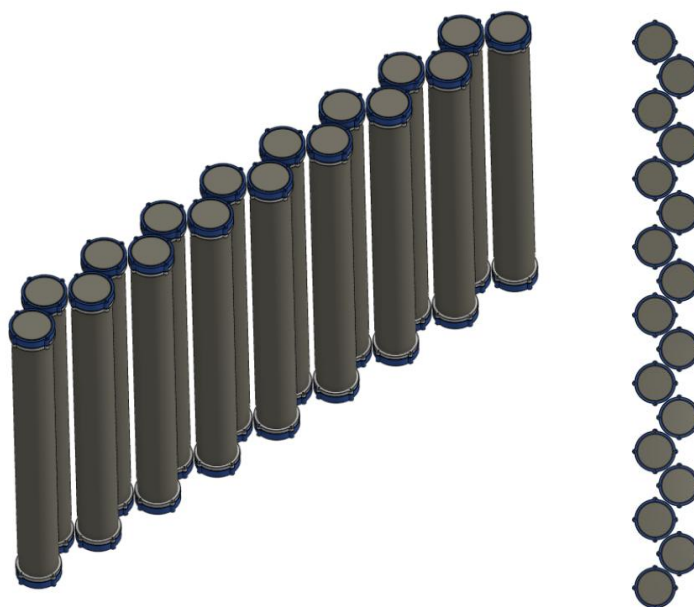


Figure 4. Design baseline

3.2.1 Core Design

The internal architecture of each module was developed following DfAM principles, taking advantage of the geometric freedom offered by LPBF technology. The core consists of a Triply Periodic Minimal Surface (TPMS) structure, which enables the generation of highly interconnected flow paths while maintaining a large wetted surface within a compact volume.

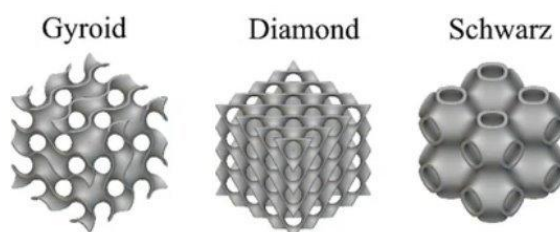


Figure 5. TPMS structures

Several TPMS topologies commonly reported in thermal management applications were initially evaluated, including Gyroid, Diamond, and Schwarz configurations. A preliminary CFD assessment was performed to characterize the hydraulic behaviour of each topology, focusing on the relationship between cell size and pressure losses. This analysis provided a quantitative understanding of the trade-off between flow resistance and geometric complexity, allowing the different alternatives to be ranked from a fluid dynamic perspective.

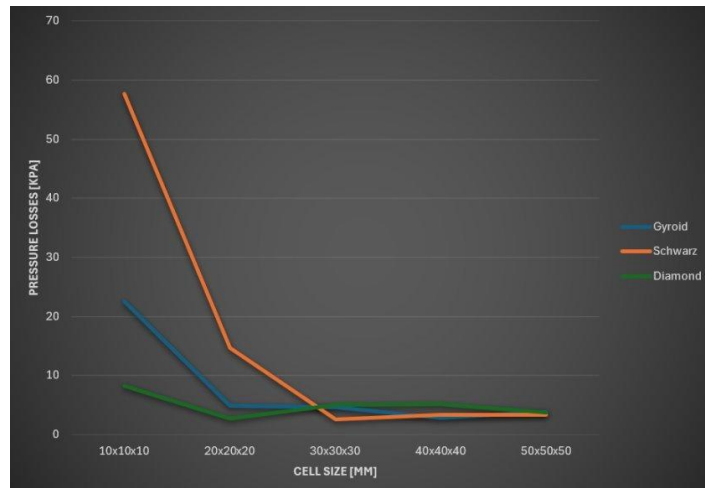


Figure 6. TPMS hydraulic losses

The results identified the Diamond topology as the most suitable candidate for the present application. Compared with the other evaluated structures, it demonstrated lower hydraulic resistance while preserving a highly interconnected geometry capable of promoting flow mixing and enhancing the interaction between the coolant and the surrounding solid structure.

In addition to the internal Diamond TPMS core, a Body-Centered Cubic (BCC) lattice structure was integrated on the external surface of the module, directly exposed to the airflow. This lattice acts as an extended surface, increasing the available solid-air interface and promoting enhanced convective heat transfer. The selected BCC topology also provides advantages regarding LPBF manufacturing and structural efficiency, aspects that will be further addressed in the following sections.

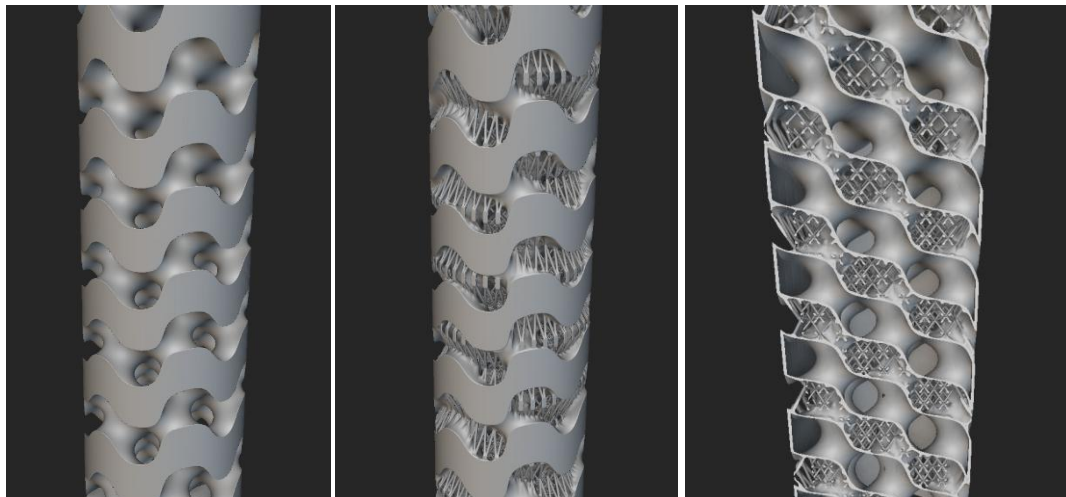


Figure 7. Left: Module without lattice structure. Center: Module with external lattice structure. Right: Cross-sectional view of the module showing the integrated lattice architecture.

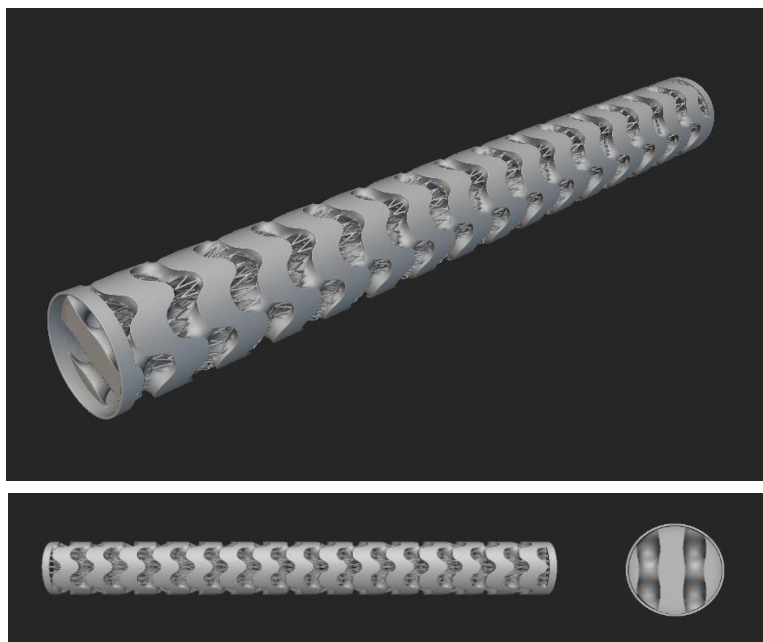


Figure 8. Module design proposal

The proposed heat exchanger module features a 90 mm diameter cylindrical architecture, selected to provide a suitable balance between hydraulic performance and system integration requirements. This dimension is consistent with the connection sizes commonly used in high-power engine cooling systems and facilitates integration within existing thermal management layouts while maintaining acceptable coolant velocities and pressure losses. A module length of 800 mm was selected in order to maximize the utilization of the frontal area available within the design envelope defined by the system requirements.

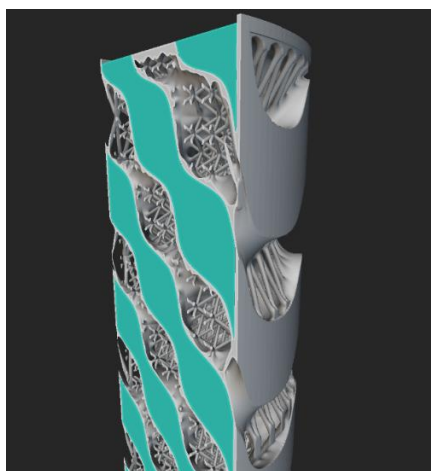


Figure 9. Coolant path

The proposed module constitutes the basic building block of the thermal management architecture. Through the CFD and CHT simulations presented in the following sections, the number of modules required for each cooling circuit, as well as their optimal hydraulic arrangement and interconnection strategy, will be determined. This assessment will ensure that the final system configuration satisfies the thermal and hydraulic requirements defined for both the MT and HT circuits while preserving the scalability and modularity objectives established within the H2UPSCALE project.

The cross-sectional view presented in Figure 9 illustrates the internal coolant path (blue) together with the lattice-based core architecture, providing insight into the heat exchanger internal design and flow distribution strategy.

3.2.3 Mounting Features and Connections

The interconnection of the individual modules will be defined according to the specific requirements of each application and corresponding power node (Node 1, Node 2, or Node 3). Taking advantage of the flexibility provided by the modular architecture, the overall arrangement, orientation, and integration of the heat exchanger assembly can be easily adapted to different installation environments and thermal management layouts.

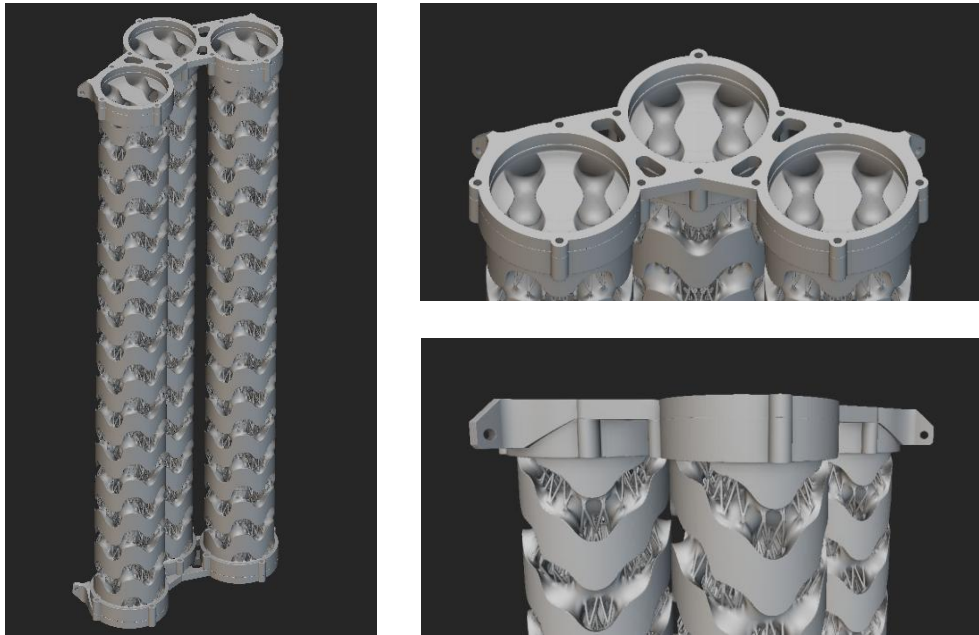


Figure 10. Mounting features and connections

To support this adaptability, the mounting interfaces were designed to provide maximum integration flexibility. The fixation points enable straightforward installation across a wide range of supporting structures and packaging configurations, allowing the same heat exchanger module to be deployed in different applications without modifications to the module itself.

A dedicated mounting ring was developed to provide the mechanical interface between the HEX module, the supporting structure, and the hydraulic connections. Manufactured as an independent component, the ring can be adapted to different assembly layouts and module combinations, enabling the integration of single-module or multi-module configurations according to the cooling requirements of each application.

This approach preserves a standardized heat exchanger module while allowing the overall system architecture to be configured and scaled through application-specific mounting and connection elements.

3.3 Design Simulation

To validate the proposed heat exchanger concept, Computational Fluid Dynamics (CFD) simulations were performed. Given the need to simultaneously resolve fluid flow and heat transfer phenomena within both the fluid and solid domains, a Conjugate Heat Transfer (CHT) approach was selected as the most suitable numerical methodology. The numerical assessment of the proposed heat exchanger presents significant computational challenges due to the combination of internal and external fluid domains, the complex TPMS-based geometry of the core, and the high mesh

density required to accurately resolve the thermal and hydraulic behaviour of the component. As a consequence, a dedicated simulation strategy was developed to reduce the computational requirements while maintaining sufficient accuracy for design validation.

The proposed heat exchanger module has a total axial length of 800 mm and is characterized by a repetitive cross-sectional architecture with constant geometric features along its main axis. Based on this characteristic, a representative 100 mm long section was selected as the reference computational domain for the CFD analyses. In addition to significantly reducing the computational cost of the CHT simulations, this section length was intentionally selected to match the geometry of the experimental demonstrator planned for fabrication and testing during the subsequent stages of the H2UPSCALE project. This approach ensures consistency between the numerical and experimental activities, facilitating the validation of the simulation methodology and the comparison of thermal and hydraulic performance results.

For the hydraulic assessment, pressure losses can be directly extrapolated from the simulated section to the complete module. Since the geometry and flow characteristics remain unchanged along the axial direction, the total pressure drop of the full-length heat exchanger can be estimated by linearly summing the pressure losses obtained for each individual segment. Consequently, the pressure drop of the complete 800 mm module corresponds to eight times the pressure drop predicted for the 100 mm section.

The thermal behavior, however, cannot be extrapolated using the same linear approach. As heat transfer depends on the local temperature difference between the coolant, the solid structure, and the surrounding airflow, the thermal performance evolves non-linearly along the length of the heat exchanger. To account for this effect, a sequential simulation methodology was adopted. The outlet coolant temperature obtained from a given section is used as the inlet condition for the subsequent section, allowing the progressive reduction of the temperature gradient along the module length to be accurately captured. By repeating this procedure for four consecutive sections, the thermal performance of the complete heat exchanger can be reconstructed while maintaining a computationally efficient simulation framework.

The following sections describe the methodology adopted for the simulation process, including the definition of the design point, the simulation model setup, and the evaluation of the obtained results.

3.3.1 Design point definition

The design point definition is a key step in the simulation process, as it establishes the reference conditions used to evaluate the HEX performance and validate compliance with the design targets. For this purpose, a worst-case scenario was selected, corresponding to the most demanding operating conditions expected during system operation:

- Ambient temperature: 40°C
- Altitude: 1500 m above sea level
- MT circuit thermal load: 45 kW
- HT circuit thermal load: 380 kW

These conditions were used as the reference case for the subsequent CHT simulations and design validation activities.

3.3.2 CHT Simulation model Setu

3.3.2.1 Domain and geometry, Mesh generation

The implicit model of the proposed heat exchanger module was imported into the CFD environment and processed for the generation of the computational domains required for the Conjugate Heat Transfer (CHT) analysis. As previously described, the simulations were performed on a representative 100 mm long section corresponding to half of the physical module by exploiting the longitudinal symmetry of the design.

Two fluid domains were generated from the solid geometry: the internal coolant domain, corresponding to the flow passages within the heat exchanger core, and the external air domain surrounding the module. These domains are illustrated in Figure 11

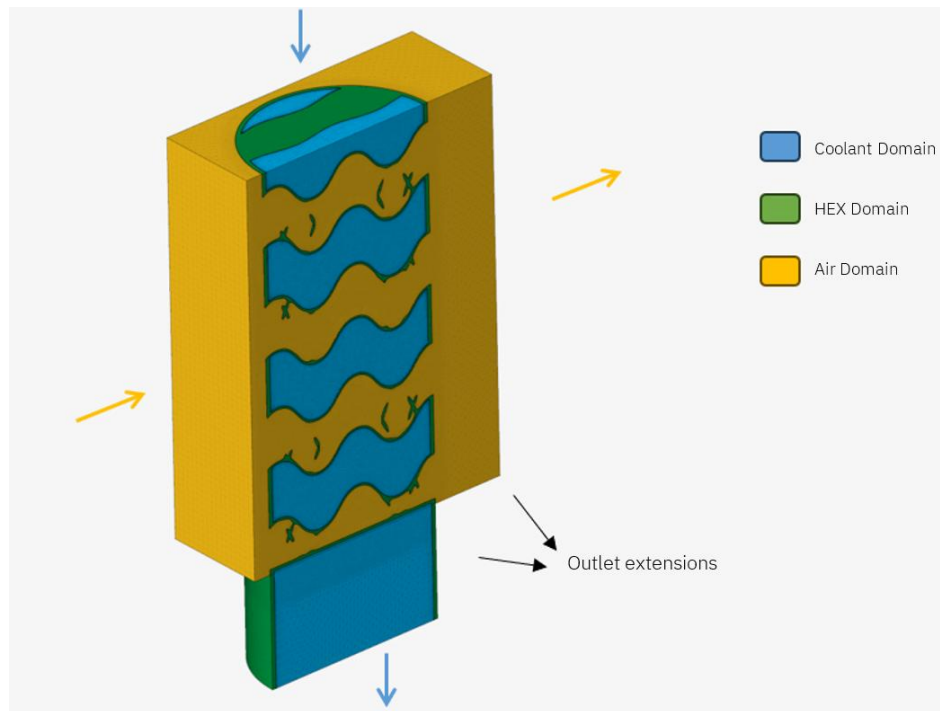


Figure 11. CHT Domains

Additional geometric extension was incorporated downstream of the coolant outlet. This extension consists of a continuation of the internal flow channel beyond the active heat transfer region and was introduced exclusively for numerical purposes. Its primary function is to prevent reverse-flow and recirculation effects at the outlet boundary condition, which can negatively affect solver stability and convergence during the simulation process.

A similar approach was adopted for the external air domain, which was extended downstream of the heat exchanger outlet. The extended air region provides sufficient space for flow development after passing through the module, minimizing potential numerical disturbances at the outlet boundary and improving overall solution stability.

The inclusion of this extension does not influence the predicted thermal performance of the heat exchanger, as no heat exchange takes place within this region. Since the extended section is not exposed to the external airflow domain, the coolant temperature remains essentially unchanged along its length. Furthermore, the associated hydraulic losses are negligible compared to those generated within the active heat transfer core and therefore do not affect the overall pressure drop assessment.

Following domain generation, a volume mesh was created for both fluid regions and the solid domain, ensuring proper resolution of the complex TPMS-based internal geometry as well as the fluid-solid interfaces governing the conjugate heat transfer process. Local mesh refinements were applied in regions characterized by high velocity and thermal gradients, achieving an average element size of 0.8 mm and a minimum element size of 0.1 mm.

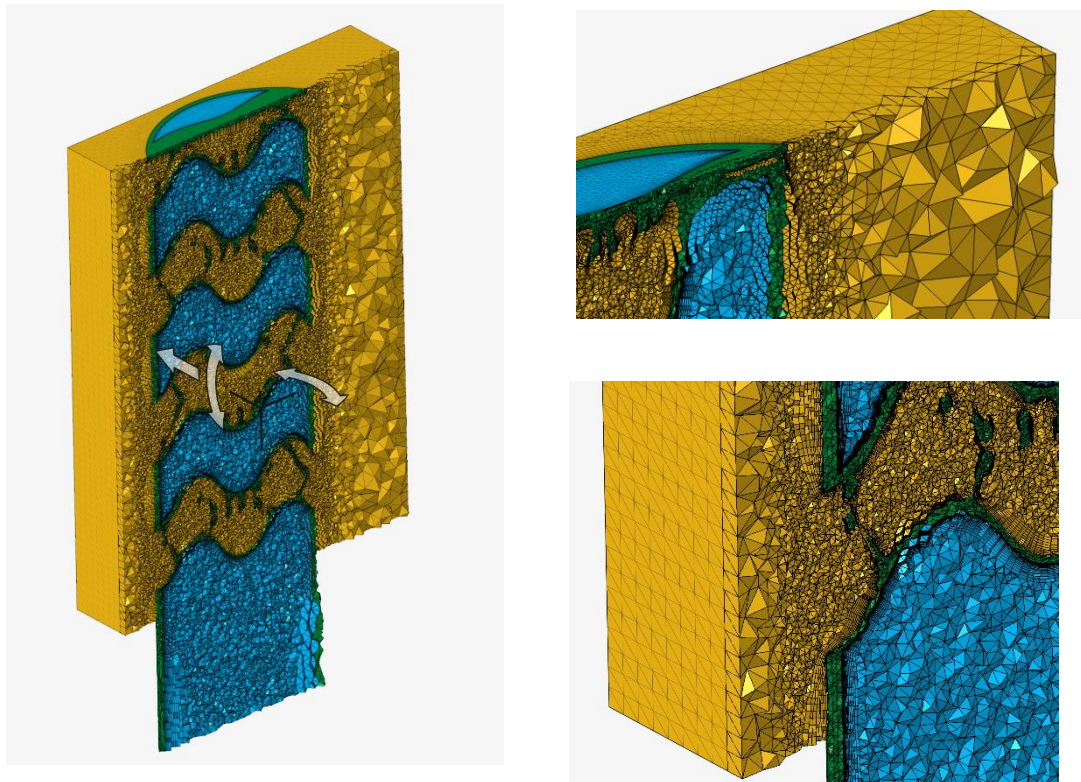


Figure 12. CHT mesh

3.3.2.2 **Boundary conditions and solver settings**

The CHT simulations were performed using the operating conditions defined in WP3 for the MT and HT cooling circuits. The boundary conditions applied to the computational models are summarized below:

HT HEX coolant side

- Inlet temperature: 88 °C
- Volumetric flow rate: Total 420 L/min

Following the first design iterations and CFD assessments, it was determined that the total coolant flow rate must be distributed among multiple heat exchanger modules connected in parallel in order to maintain the hydraulic losses within acceptable limits. The optimal configuration identified consists of 7 parallel branches. Consequently, the flow rate assigned to each individual module for the present simulations corresponds to 1 L/seg, obtained by equally distributing the total circuit flow among the parallel branches.

MT HEX coolant side

- Inlet temperature: 65 °C
- Volumetric flow rate: Total 75 L/min

In contrast to the HT circuit, the hydraulic assessment indicated that the MT coolant flow can be processed through a single module without exceeding the established pressure drop limits.

Air side (both cases)

- Inlet temperature: 40 °C

- Mass flow rate: 20 kg/s

The air mass flow rate initially considered for the design was 12 kg/s, according to the requirements defined in WP3. However, following multiple CFD design iterations and thermal performance assessments, it was determined that a higher airflow rate was required to achieve acceptable heat rejection performance while maintaining the proposed modular architecture. Consequently, an air mass flow rate of 20 kg/s was adopted for the final simulations presented in this report.

The airflow assigned to each simulation was calculated by distributing the total air mass flow rate equally among the heat exchanger modules required by the analysed configuration. The corresponding flow rate applied to the computational domain therefore represents the airflow passing through a single module section under the assumption of uniform airflow distribution across the complete assembly.

In addition, slip boundary conditions were applied to the external faces of the air domain representing the continuation of the surrounding environment, minimizing artificial wall effects and allowing the airflow to develop naturally around the heat exchanger, while a symmetry boundary condition was imposed at the model cutting plane as a consequence of the half-model approach adopted in this study.

Lastly, the **Spalart-Allmaras turbulence model** was adopted for all simulations due to its good convergence characteristics and computational efficiency. Its use allowed a systematic comparison of multiple design alternatives under a consistent numerical framework while maintaining a reasonable computational cost.

3.3.3 CHT Simulation results

The selected numerical setup provided robust convergence for all simulated cases. Stable residual trends and converged thermal and hydraulic performance indicators were achieved, ensuring that the simulation results can be considered reliable for the evaluation and comparison of the proposed heat exchanger configurations. The corresponding convergence histories are shown below.

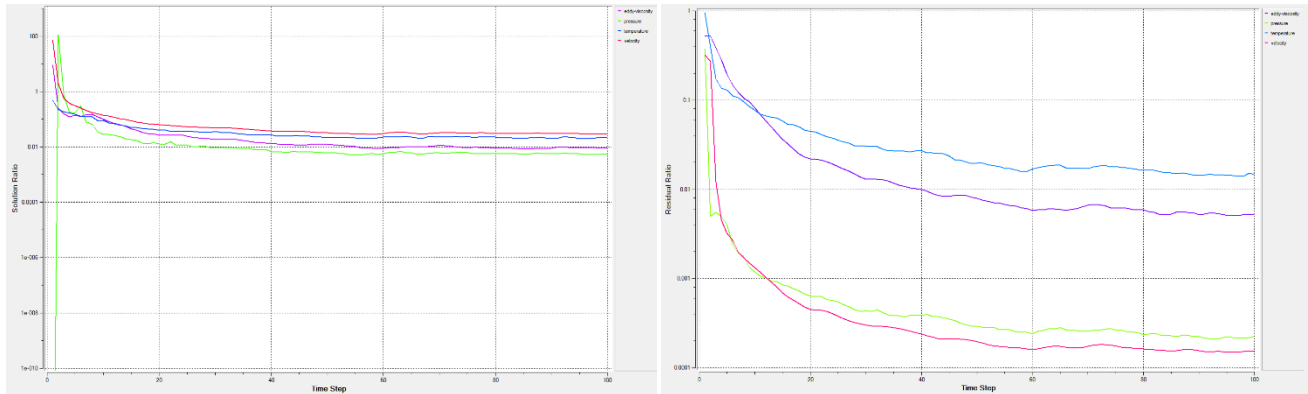


Figure 13. Solution and Residual Ratio after 100 time steps

3.3.3.1 Hydraulic performance results

The hydraulic performance of the proposed heat exchanger module was evaluated for both cooling circuits under their corresponding coolant flow conditions. The pressure drop obtained across the simulated 100 mm module section is summarized below:

HT HEX

- Coolant flow rate: 1 L/s
- Pressure drop: 3,4 kPa

MT HEX

- Coolant flow rate: 1,25 L/s
- Pressure drop: 3,8 kPa

3.3.3.2 Thermal performance results

The tables below summarize the results obtained from the successive simulations performed for each module section. As described previously, the complete thermal performance of the heat exchanger was reconstructed by sequentially analysing the individual 100 mm sections and using the outlet conditions of each section as the inlet conditions for the subsequent one.

HT HEX

- Coolant Inlet Temp: 88°C
- Coolant Outlet Temp: 86,3°C
- Delta Temp: 1,7°C

MT HEX

- Coolant Inlet Temp: 65°C
- Coolant Outlet Temp: 63,6°C
- Delta Temp: 1,4°C

3.4 Design assessment

The thermal performance of the HEX modules was evaluated through an energy balance based on the coolant temperature drop, flow rate, and thermophysical properties of the working fluid.

The outlet temp was calculated according to:

$$\dot{Q} = \dot{m} \cdot C_p \cdot (T_{in} - T_{out})$$

(where C_p is the specific heat capacity of the coolant formulation developed within the project)

Coolant properties:

- C_p :
 $3.4 \times 10^6 \text{ mJ}/(\text{kg} \cdot ^\circ\text{C})$
- Density: $1.0515 \times 10^{-6} \text{ kg}/\text{mm}^3$

HT HEX

Coolant inlet temperature: 88 °C
Volumetric flow rate: 7 L/s
Objective Heat rejection: 380kW

→ HT Coolant outlet temperature: 72,4 °C

MT HEX

Coolant inlet temperature: 65 °C
Volumetric flow rate: 1,25 L/s
Objective Heat rejection: 45kW

→ MT Coolant outlet temperature: 54,7 °C

3.4.1 MT HEX assessment

Based on the simulations, approximately **7** heat exchanger sections are required to achieve the target coolant outlet temperature. Considering the additive nature of the hydraulic losses along the module length, the total pressure drop associated with the complete heat exchanger configuration was estimated by summing the pressure losses of the individual sections.

The resulting total pressure drop was:
 $\Delta P = 26,6 \text{ kPa}$

3.4.2 HT HEX assessment

Based on the simulations, approximately **10** heat exchanger sections are required to achieve the target coolant outlet temperature. Considering the additive nature of the hydraulic losses along the module length, the total pressure drop associated with the complete heat exchanger configuration was estimated by summing the pressure losses of the individual sections.

The resulting total pressure drop was:
 $\Delta P = 34 \text{ kPa}$

In this way, the thermal dissipation capacity of each heat exchanger module can be determined, confirming the number of module sections required to fulfill the thermal performance targets established within the H2UPSCALE project.

4. LPBF printing parameters and surface roughness - T7.1.4

After the selection of material 4 and the definition of stable bulk manufacturing condition, the next activity was focused on the surface quality of the L-PBF manufactured material.

Surface roughness is an important parameter for the HeX because the final component contains complex internal surfaces that will be in contact with the coolant. Therefore, the objective of this activity was to study the relationship between the L-PBF manufacturing conditions and the resulting surface roughness, using simple geometries that could be easily manufactured and characterized.

Selection of the layer thickness

The initial experimental plan considered the manufacturing of samples using 30 μm and 60 μm layer thicknesses. The objective was to compare the influence of layer thickness on surface roughness and manufacturing time.

However, after the selection of material 4 and the development of the first stable manufacturing condition, the experimental work was focused on a 60 μm layer thickness.

As described in Section 7.1.2, the manufacturer of the LPBF equipment available at the technological centre does not yet provide a developed and optimized material profile specifically for material 4. Developing an additional 30 μm material condition would therefore require a new material parameter development stage before the surface roughness study.

In addition, the final demonstrator is a heat exchanger with a complex geometry and a significant manufacturing volume. For this type of component, LPBF productivity is an important consideration. A 60 μm layer thickness reduces the total number of layers and consequently the manufacturing time compared with a 30 μm layer thickness.

For these reasons, 60 μm was selected as the layer thickness for the experimental development. The previously defined bulk condition was maintained, and the experimental work was focused on the manufacturing parameters directly related to surface quality.

DoE_01 – Comparison of material profiles

The first Design of Experiments (DoE_01) was defined to study the influence of the L-PBF material profile on the roughness of material 4.

For this purpose, simple geometries with different inclination angles with respect to the build platform were manufactured. The sample design allows the upskin and downskin surfaces to be characterised independently and the evolution of surface roughness as a function of the build angle to be studied.

The main objective of DoE_01 was to compare two different manufacturing profiles for material 4:

- Profile based on material 2: this profile was used as the starting point during the initial development of material 4. It allowed material 4 to be successfully manufactured but did not include specific edge parameters.

- Material 4 profile developed by Renishaw: this profile was specifically developed for material 4 by the LPBF technology manufacturer. In addition to using a different bulk condition, this profile includes specific edge parameters developed to improve the processing of the surfaces.

Therefore, the study compares the initial manufacturing condition with a profile specifically developed for material 4 and evaluates its influence on surface roughness.



Figure 14. Geometries used in DoE_01 to study the surface roughness of the upskin and downskin surfaces as a function of the build angle.

For the material 4 profile developed by Renishaw, a total of 13 samples were manufactured, covering build angles from 25° to 55°. This set of samples provides a more detailed evaluation of the evolution of surface roughness with the build angle.

For the profile based on material 2, a total of 5 samples were manufactured at 30°, 45°, 47.5°, 50°, 55°.

For both profiles, the upskin and downskin surfaces were considered for the subsequent surface characterization.



Figure 15. Material 4 samples manufactured using the two material profiles evaluated in DoE_01.

Table 5 Comparison of the material profiles and experimental conditions used in DoE_01.

Parameter	Profile based on material 2	Material 4 profile developed by Renishaw
Manufactured material	Material 4	Material 4
Layer thickness	60 µm	60 µm
Hatch distance	0.13 mm	0.10 mm
Hatch power	370 W	400 W
Hatch point distance	28 µm	30 µm
Hatch exposure time	20 µs	20 µs
Equivalent scan speed	1400 mm/s	1500 mm/s
Number of samples	5	13
Build angles	30° / 45° / 47.5° / 50° / 55°	25°–55°
Surfaces to be characterised	Upskin / Downskin	Upskin / Downskin

It is important to highlight that the manufactured material was material 4 in both cases. Material 2 was only used as the base material profile for the configuration of the initial material 4 manufacturing condition.

The profile specifically developed for material 4 also includes edge parameters for the processing of part surfaces. These parameters are part of the material profile development carried out by the LPBF technology manufacturer and are subject to confidentiality. Therefore, their specific values are not reported in this deliverable.

DoE_01 was therefore focused on the experimental comparison of the surface quality obtained with both material profiles, using surface roughness as the main response. For the building angles available in both profiles, a direct comparison between the two manufacturing strategies can be made. In addition, the larger number of angles manufactured with the material 4 profile allows the influence of surface inclination to be studied in more detail.

After manufacturing and identification of the samples, the upskin and downskin surfaces were characterized to quantify the surface roughness obtained with each material profile.

Surface roughness characterisation – DoE_01

After manufacturing the samples corresponding to the two process profiles, surface roughness characterisation was performed to quantify the differences obtained between both manufacturing strategies.

The characterisation was performed by contact profilometry, independently evaluating the Upskin and Downskin surfaces of the samples. A measurement length of approximately 5 mm was used, and Ra was selected as the main parameter to compare the surface quality obtained with the different manufacturing profiles. The characterisation reports show measurement lengths close to 5 mm and approximately 6146 recorded points per profile.

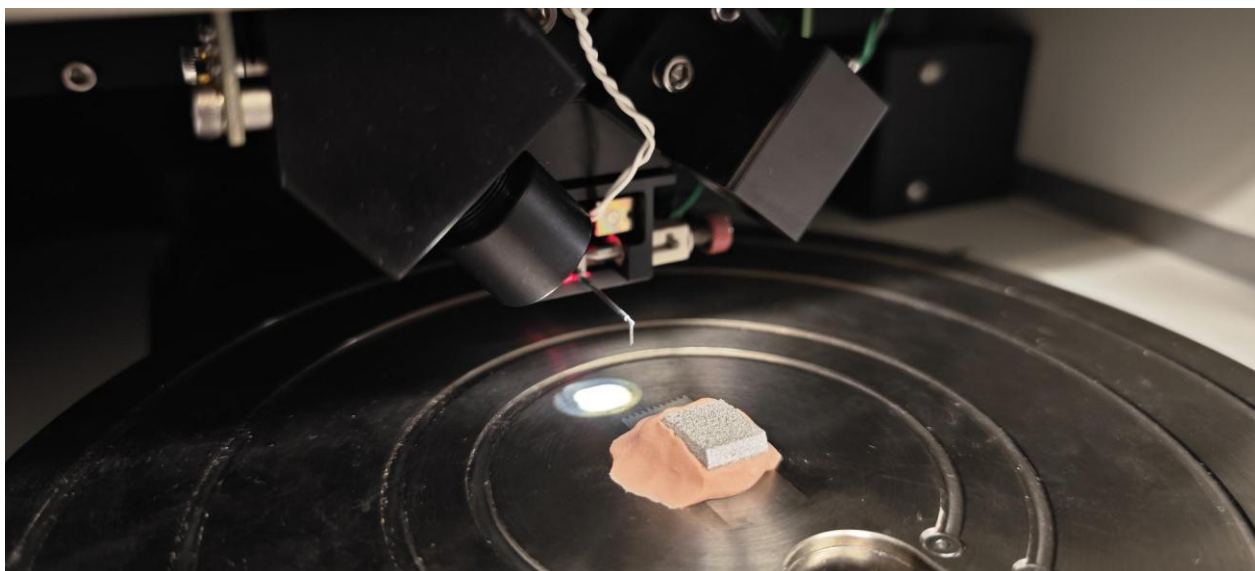


Figure 16. Profilometry equipment and sample positioning.

The main objective of this characterisation was to evaluate the effect of the specific development of the material 4 profile on surface quality. As previously described, the initial profile based on material 2 was mainly used to obtain a stable manufacturing condition for material 4. This profile was focused on material consolidation through the bulk parameters and did not include specific edge parameters to control surface roughness.

Despite the relatively high surface roughness obtained with this initial strategy, the samples were successfully manufactured and were subsequently used for corrosion testing, where material 4 showed favourable behaviour under the evaluated conditions. Therefore, once the initial manufacturing feasibility of the material was demonstrated, the next objective was to improve its surface quality using a profile specifically developed for material 4.

The profile developed by Renishaw includes specific parameters for edge processing, together with a modification of the main bulk parameters. The specific values of the edge parameters are not reported due to confidentiality. However, the experimental comparison of the resulting surface roughness allows the overall effect of this manufacturing strategy to be evaluated.

The results obtained for the initial profile based on material 2 are summarized in table 6.

Table 6 Surface roughness results obtained for the profile based on material 2 as a function of build angle.

Sample	Build angle (°)	Upskin Ra (µm)	Downskin Ra (µm)
Material 2_03	30	25.16	40.36
Material 2_09	45	36.06	47.14
Material 2_10	47.5	27.53	52.35
Material 2_11	50	35.17	47.14
Material 2_12	55	27.77	41.28

The initial profile presented an average value of Ra = 30.34 µm for Upskin and Ra = 45.65 µm for Downskin. Under the evaluated conditions, the Downskin surfaces presented higher roughness than the Upskin surfaces, identifying this orientation as the more critical surface condition.

The results obtained using the profile specifically developed for material 4 are presented in table 7.

Table 7 Surface roughness results obtained for the profile specifically developed for material 4 as a function of build angle.

Sample	Build angle (°)	Upskin Ra (µm)	Downskin Ra (µm)
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Material 4_01	25	17.32	55.13
Material 4_02	27.5	21.05	80.86*
Material 4_03	30	18.88	47.13
Material 4_04	32.5	17.70	41.09
Material 4_05	35	12.46	52.35
Material 4_06	37.5	18.04	52.46
Material 4_07	40	23.38	56.65
Material 4_08	42.5	27.28	34.85
Material 4_09	45	14.88	27.56
Material 4_10	47.5	24.72	34.36
Material 4_11	50	20.01	35.32
Material 4_12	52.5	16.71	41.35
Material 4_13	55	19.78	22.53

The Downskin value obtained for material 4_02 (80.86 μm) is significantly higher than the other measurements and is therefore considered a measurement requiring further verification. Until this measurement is confirmed, it is not used to establish trends or to calculate the representative average Downskin roughness. The original reported value is maintained in the table for traceability.

Provisionally excluding this measurement, the average Downskin roughness for the remaining material 4 samples is approximately $R_a = 41.73 \mu\text{m}$, while the average Upskin roughness for the 13 samples is $R_a = 19.40 \mu\text{m}$.

The Upskin surfaces showed relatively low roughness values and lower variability, with R_a values ranging approximately from 12.5 to 27.3 μm . In contrast, the Downskin surfaces presented higher roughness and a stronger dependence on the build orientation.

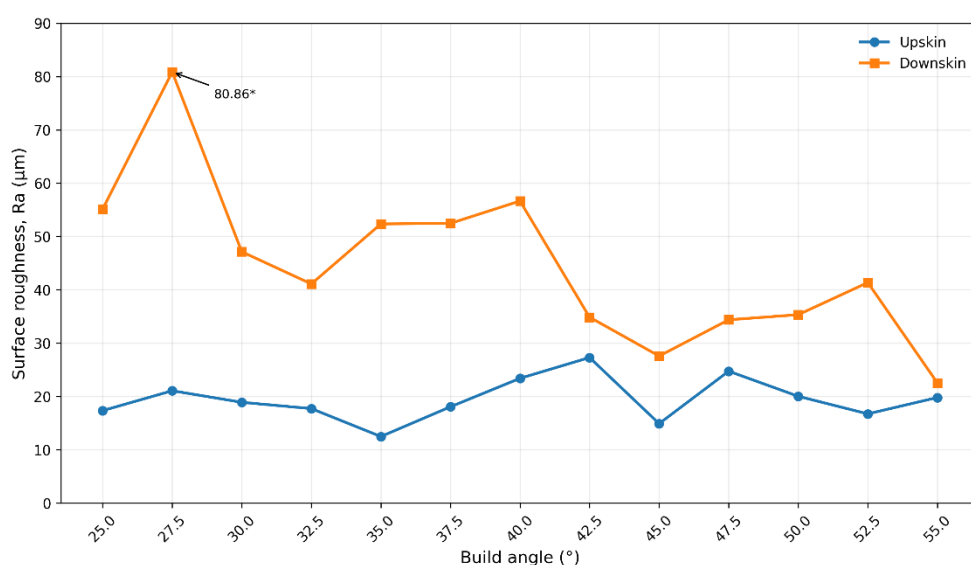


Figure 17. Evolution of the Upskin and Downskin surface roughness as a function of build angle for the manufacturing profiles evaluated in DoE_01

The comparison of the results shows a clear improvement in the Upskin surfaces when using the profile specifically developed for material 4. The average R_a decreased from 30.34 μm for the profile based on material 2 to 19.40 μm for the material 4 profile, corresponding to a reduction of approximately 36%.

For the Downskin surfaces, the roughness showed a stronger dependence on the build angle. Since the two profiles do not include the same number of samples or build angles, the comparison should mainly be performed using the common conditions rather than only considering the overall average values.

The DoE_01 results therefore confirm that the development of a specific profile for material 4 can clearly improve the surface quality, particularly for the Upskin surfaces. However, the Downskin surfaces still present higher roughness values and larger variability.

For this reason, the second Design of Experiments, DoE_02, was specifically focused on the optimisation of the parameters acting on the Downskin surfaces, with the objective of reducing their surface roughness while maintaining the 60 µm layer thickness selected for the manufacturing of the HeX.

DoE_02 – Downskin parameter optimisation

Based on the results obtained in DoE_01, a second Design of Experiments DoE_02 was defined, specifically focused on improving the Downskin surfaces of material 4.

The characterisation performed in DoE_01 showed that the profile specifically developed for material 4 improves the surface quality, especially for the Upskin surfaces. However, the Downskin surfaces still presented higher roughness values and larger variability, identifying this surface condition as having the greatest potential for further improvement.

Although the material 4 profile includes specific parameters developed by Renishaw for edge processing, the specific Downskin strategy has not yet developed and optimised parameters for material 4.

For this reason, DoE_02 was defined as a second development stage with two main objectives, to improve the quality of the Downskin surfaces for the future manufacturing of the HeX and to generate experimental knowledge that can contribute to the further development of the material 4 profile together with the LPBF technology manufacturer.

Selection of the experimental condition

For this second study, a geometry with a 45° build angle was selected. The use of a single angle allows the geometrical condition to remain constant, and the study focuses on the influence of the specific Downskin manufacturing parameters.

The Skin Activation Angle was set at 45°, ensuring that the Downskin strategy was applied to the surface under study.

The number of layers where the Downskin strategy was applied was fixed at 7 layers for all five experimental conditions. In this way, the number of layers was kept constant and was not introduced as an additional variable in the DoE.

The parameter selected as the experimental variable was Downskin Hatch Power, while the remaining main manufacturing conditions were kept constant.



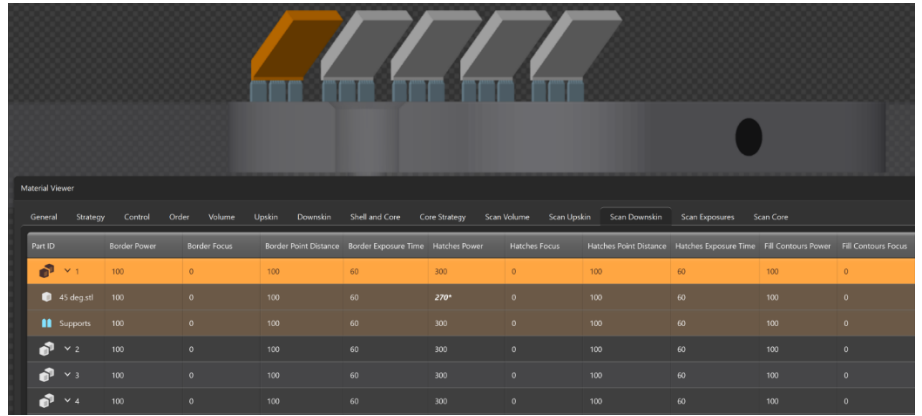
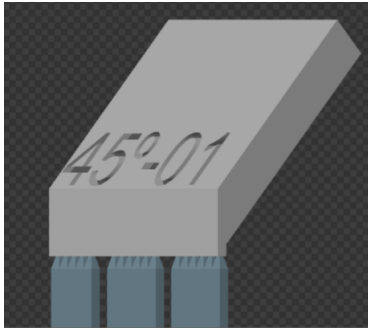


Figura 18: Material 4 geometry manufactured at 45° and used for the study of the Downskin manufacturing parameters in DoE_02

Downskin hatch power variation.

Downskin Hatch Power was selected as the main variable for DoE_02. Five power levels were evaluated: 270 W, 240 W, 210 W, 180 W, 150 W.

The power was progressively reduced using constant 30 W intervals, allowing the influence of Downskin Hatch Power on the surface quality to be evaluated under controlled conditions.

A total of five material 4 samples were manufactured. All samples were manufactured at a 45° build angle and using 7 Downskin layers, while only the Downskin Hatch Power was modified between the different experimental conditions.

Table 8 Experimental conditions used in DoE_02 to study the influence of Downskin Hatch Power.

Sample	Build angle (°)	Skin Activation Angle (°)	Downskin layers	Downskin Hatch Power (W)
Material 4_01	45	45	7	270
Material 4_02	45	45	7	240
Material 4_03	45	45	7	210
Material 4_04	45	45	7	180
Material 4_05	45	45	7	150

Manufacturing of the samples

The five experimental conditions were manufactured by LPBF using material 4. All samples were successfully manufactured, allowing the subsequent surface characterization to be performed.



Figure 19. LPBF manufacturing of the material 4 samples used in DoE_02 for the study of the Downskin parameters.

Surface roughness characterization

After manufacturing, the Downskin surfaces of the five samples were characterized by profilometry, following the same methodology previously used in DoE_01.

The Ra parameter was used as the main indicator of surface roughness. In addition, 3D surface topography characterization was performed to complement the analysis using the areal roughness parameter Sa.

The results obtained are summarized in the following table 9.

Table 9 Downskin surface roughness results obtained for the different conditions evaluated in DoE_02.

Sample	Downskin Hatch Power (W)	Build angle (°)	Ra (μm)	Ra Std. dev. (μm)	Sa (μm)
Material 4_01	270	45	21.8	3.37	65.9
Material 4_02	240	45	20.7	0.82	54.9
Material 4_03	210	45	20.8	2.02	48.6
Material 4_04	180	45	19.2	4.09	59.4
Material 4_05	150	45	21.0	1.05	67.7

Influence of Downskin hatch power

The results show that Downskin Hatch Power has an influence on the obtained surface roughness, although a completely linear relationship between the applied power and Ra was not observed.

When the power was reduced from 270 W to 180 W, the mean Ra value decreased from 21.8 μm to 19.2 μm, representing an approximate reduction of 12%.

The 180 W condition showed the lowest mean Ra value among the five conditions studied. However, this condition also presented the highest variability, with a standard deviation of 4.09 μm.

A further reduction in power to 150 W did not produce an additional improvement, and the Ra value increased again to 21.0 μm.

Therefore, the results indicate that reducing the Downskin Hatch Power can improve the surface quality within a specific range. However, a continuous reduction in power does not necessarily produce a continuous reduction in surface roughness.

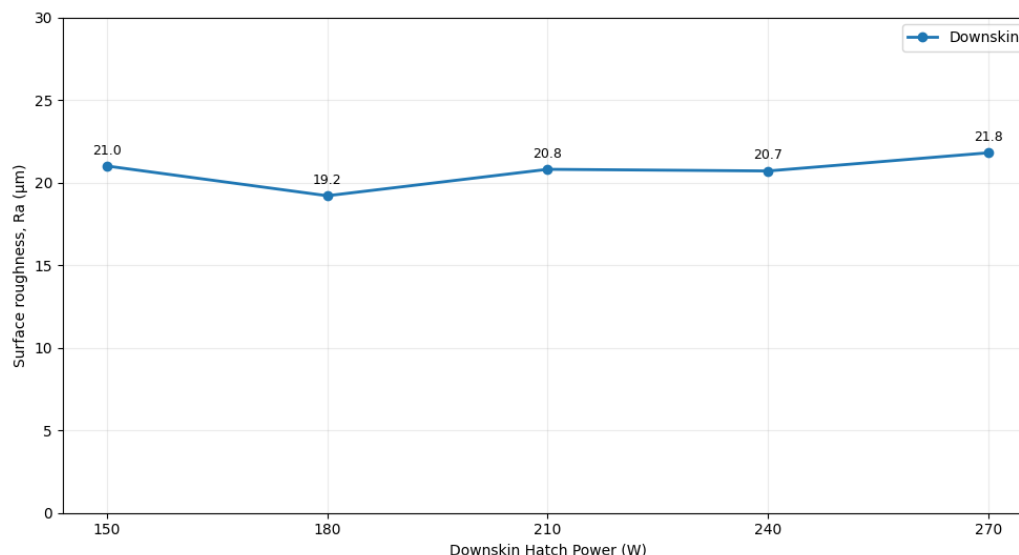


Figure 20. Influence of Downskin Hatch Power on the mean surface roughness (Ra) of material 4 at a 45° build angle

3D surface topography analysis

The 3D surface topography characterization was used to complement the Ra results and to evaluate the surface using the areal roughness parameter Sa.

The results showed Sa values between 48.6 and 67.7 µm. The 210 W condition presented the lowest Sa value, 48.6 µm, while the 150 W condition presented the highest value, 67.7 µm.

The comparison between the 3D surface topographies of these two conditions allows the differences in the distribution of the surface irregularities to be observed.

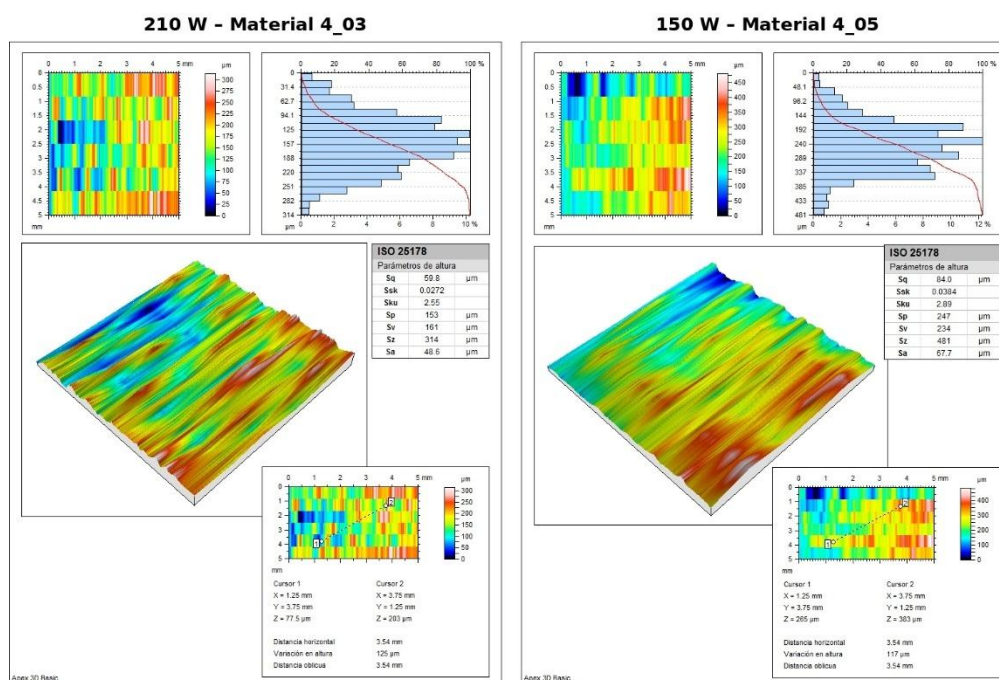


Figure 21. Comparison of the Downskin surface topography obtained for Material 4 using 210 W and 150 W Downskin Hatch Power.

DoE_02 results and conclusions

The results obtained in DoE_02 show that the modification of the Downskin Hatch Power allows the rough surface of material 4 to be controlled. Within the studied range, the 180 W condition presented the lowest mean Ra value (19.2 μm), while the 210 W condition presented the lowest Sa value (48.6 μm). These results identify the range between 180W and 210W as a process window of particular interest for the further development of the Downskin strategy.

For the final HeX application, the objective is not only to minimize surface roughness, but to obtain a controlled surface suitable for the operating conditions. A certain level of roughness can improve the interaction between the fluid and the surface, while excessively high roughness can negatively affect the fluid flow. Therefore, the development will focus on achieving a controlled surface roughness, looking for a balance between surface quality and the heat transfer requirements of the HeX.

Based on these results, the next activities will continue to study the process window between 180 W and 210 W. In addition, a mechanical post-processing treatment by sandblasting will be evaluated as a possible strategy to modify and homogenize the surface. These activities will support the further development of the manufacturing and surface finishing conditions of material 4 for its application in the HeX.



5. HEX optimization for 3D printing - T7.1.5

As previously described during the presentation of the proposed heat exchanger concept, the design was developed following Design for Additive Manufacturing (DfAM) principles in order to fully exploit the capabilities of LPBF technology.

This approach provided several advantages from both the thermal and manufacturing perspectives:

- **Straight cylindrical envelope:** The cylindrical geometry enables a simple and robust manufacturing setup, facilitating part orientation within the build chamber and allowing a high number of modules to be efficiently nested in a single LPBF production batch. This contributes to improved manufacturing productivity and reduced production costs.
- **TPMS coolant channels:** The selected TPMS architecture provides a high surface-area-to-volume ratio while maintaining smooth and interconnected flow passages. This configuration increases the available heat transfer area without introducing excessive hydraulic losses, resulting in an efficient balance between thermal performance and pressure drop.
- **BCC lattice structure:** The external lattice incorporated on the air side of the module further increases the available heat transfer surface, enhancing the convective heat exchange with the surrounding airflow. In addition to its thermal function, the lattice also serves a structural purpose by supporting the surrounding core features during the LPBF process. This self-supporting architecture significantly reduces the need for additional support structures, simplifying manufacturing and minimizing post-processing operations associated with support removal and cleaning.

These design features demonstrate how additive manufacturing considerations were integrated from the early stages of development, enabling the creation of a compact, scalable, and highly manufacturable heat exchanger concept.

Throughout the design process, a strong emphasis was placed on adaptability and scalability, allowing the proposed concept to be tailored to different operating requirements while maintaining a common modular architecture. In addition to the main geometric parameters, such as module diameter and length, the design incorporates more advanced variables including the TPMS cell size, lattice topology, and lattice density. These parameters provide a wide design space for future optimization and performance tuning.

As a result, the proposed heat exchanger should not be considered a fixed design, but rather a flexible and evolvable platform capable of being refined as the project progresses. Future developments, simulation results, and experimental validation activities may be used to further optimize the geometry and enhance both the thermal and hydraulic performance of the system while preserving the modular philosophy established within the H2UPSCALE project.