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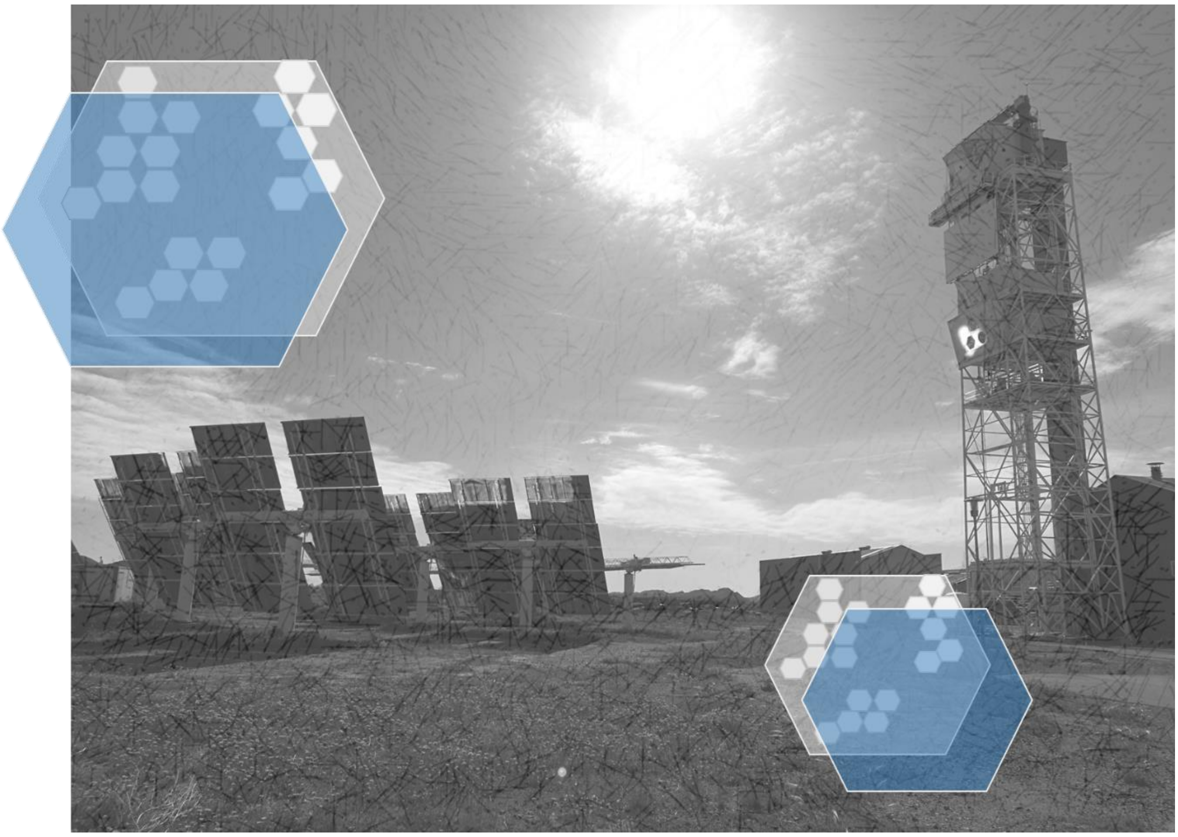

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Heat recovery-Publishable Summary Report

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Heat recovery

Another objective of the HYDROSOL-beyond project is to develop a heat recovery concept based on a novel heat exchanger (HX) architecture with the target to retrieve more than 60% of the energy content of the high temperature gases exiting the directly irradiated solar cavity reactor by preheating the incoming gas.

A single high temperature HX, which reciprocally processes water vapor and N_2, was planned to be placed downstream of the solar cavity reactor at the HYDROSOL platform located at the Plataforma Solar de Almeria in Spain. The targeted effectiveness of the new high temperature HX is 90% and it has to process fluid whose temperature could reach 1000°C.

1 Development of concept

The novel HX concept is based on engineered ceramic cellular architecture for enhancing heat transfer efficiency.

The approach that was finally chosen based on manufacturing constraints and the platform conditions was a high temperature hybrid HX, i.e. a system with the structure realized using a high temperature resistant metal alloy and with engineered ceramic cellular inserts to enhance heat transfer.

1.1 Identification of most promising material

Ceramic materials such as zirconia (ZrO_2) and silicon carbide (SiC) were promising materials for the realization of HX components. Both materials have thermo-physical and thermo-mechanical properties that are appropriate for very high temperatures (>1000 C). ZrO_2, on paper, guarantees chemical stability with the reactant and product gases (i.e. H_2O, N_2, O_2 and H_2) used in the present system, however it presents some disadvantages from the point of view of its high density, high thermal expansion coefficient, low thermal conductivity, manufacturability constraints and costs.

On the other hand, special metal alloys can be a viable alternative when the maximum temperatures of the gases entering the HX is around 1000 C.

Based on the performed study, it was decided that the HX would be a hybrid component consisting of both metallic and ceramic parts. The material that was chosen for the core structures of the HX would be reaction bonded SiC.

1.2 Identification of most promising HX technology

The selection of the most promising HX technology was performed using information gathered through a literature review study[1],[2],[3],[4]. Among the possible solutions, the one which was found to best comply with the requirements of compactness, effectiveness, low pressure drop, complete

[1] Thulukkanam, K. 2013. Heat Exchanger Design Handbook – Second Edition. CRC Press.
[2] Zhang, X., H. Keramati, M. Arie, F. Singer, R. Tiwari, A. Shooshtari, and M. Ohadi. 2018. “Recent developments in high temperature heat exchangers: a review.” Frontiers in Heat and Mass Transfer 11 (18): 1-15.
[3] Hesselgreaves, J. E. 2001. Compact heat exchangers - Selection, design and operation. Pergamon.
[4] Shah, R. K., and D. P. Sekulic. 2003. Fundamentals of heat exchanger design. Wiley.

separation of the gas streams and the flexibility in optimizing the heat transfer enhancing matrix was the plate-fin heat exchanger type with a counter-current flux configuration.

1.3 Geometry determination

For a compact HX design, the two major contributions on the overall heat transfer are given by conduction through the ceramic structured porous body that constitutes the core of the HX and thermal radiation between solid surfaces.

In particular, for very compact geometries, intermediate thermal conductivity materials (in the order of 10 $Wm^{-1}K^{-1}$) show better performance in terms of effectiveness than high-conductivity materials in the case thermal radiation is not considered as a heat transfer mechanism. However, for the high-temperature HX under investigation, in order to exploit the full potential of radiative heat transfer, high-conductivity materials (i.e. SiC) should be preferred. Also, radiative heat transfer is important when gaps are present between plates and ceramic structured porous bodies. Gaps can be either intentionally introduced in the design, to take into account thermal deformations of the different components and materials, or they can form spontaneously during normal operations. In such conditions, the detriment of the heat transfer is reduced by the presence of thermal radiation.

The conceptual design of the HHX is shown in Figure 1 constituted by a stack of plates which shape the channels for the hot and cold stream. The core region of these channels is a series of lattice tetrakaidecahedron structured bodies that would increase the heat transfer area and promote convection by disrupting the boundary layer of the flux.

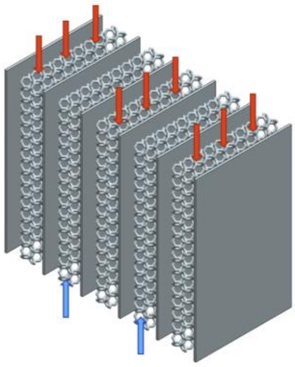

Figure 1. Representation of the plate-fin core design.[5,6]

A variety of 3-D CFD models of lattice core subdomains were simulated investigating the effect of radiation and surface emissivity on the hot channel heat transfer efficiency and its influence on the heat transfer mechanism. The size of the single tetrakaidecahedron cell is generally kept the same for the majority of the models, but the number of layers within the channel height is varied.

[5] https://ceramics.org/ceramic-tech-today/basic-science/ceramic-lattice-structures-for-high-temperature-heat-exchangers

[6] Zavattoni, Simone & Cornolti, Luca & Arrivabeni, Edoardo & Puragliesi, Riccardo & Ortona, Alberto & Barbato, Maurizio. (2021). Conceptual design and performance evaluation of an innovative high temperature ceramic heat exchanger. Journal of Physics: Conference Series. 2116. 012096. 10.1088/1742-6596/2116/1/012096.

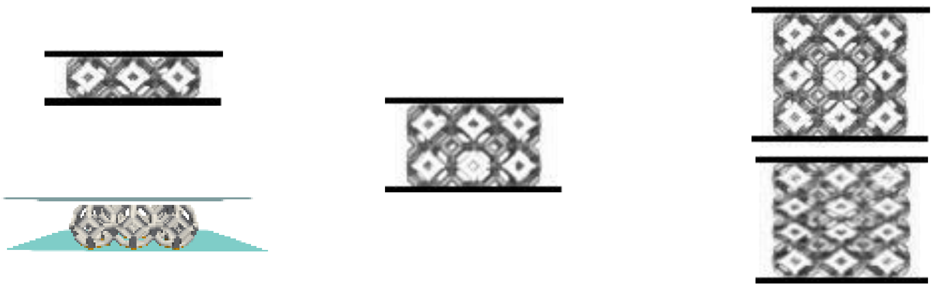

Figure 2. Frontal views of different Lattice core subdomains (1-3 layers, with and without gap, uniform and non-uniform cell size) used for deriving correlations and study radiation and its impact on the overall heat transfer

The above study led to the optimization of the geometry of the engineered ceramic structured bodies[7,8] based on a two layer structure (within the channel thickness) of the tetrakaidecahedron cell chosen for its mechanical resistance at high temperatures and relatively low pressure drop.

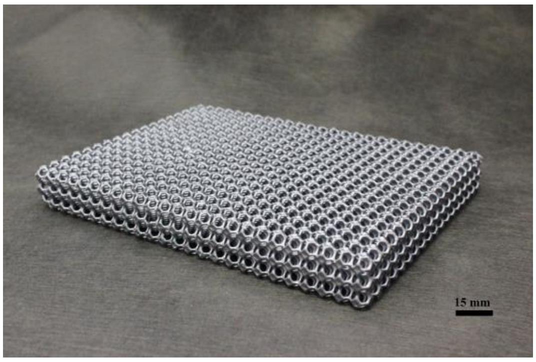

Figure 3. Manufactured ceramic lattice structure

The final geometry of the HX was optimized. For the simulations, perfect insulation towards the external environment was assumed (i.e., adiabatic condition) as well as heat losses when employing an outer layer of insulating material. Furthermore, for minimizing the thickness of the external insulating layer a different channel layout was tested, employing N hot channels and N+1 cold channels (N/N+1 layout), instead of the original N/N layout. The advantages of the N/N+1 channel layout make it the preferable solution for the final design. External temperatures at the top plate were predicted to be about 100 °C lower than the N/N channel layout.

The optimization of the manifold and duct diameters showed that large ducts were to be preferred because they minimize pressure losses and distribute the flow evenly among and within the channels.

1.4 Manufacturing of the prototype.

Before manufacturing and testing the small-scale HHX prototype, both, the thermo-mechanical resistance of the component and the appropriate testing conditions (more specifically the temperature range) were investigated by a series of numerical simulations, including computational fluid dynamics (CFD) calculations of a conjugate heat transfer (CHT) problem and finite element (FE) thermo-mechanical analyses. The two simulation platforms were loosely

[7] Szczurek, A., A. Ortona, L. Ferrari, E. Rezaei, G. Medjahdi, V. Fierro, and A. Celzard. 2015. "Carbon periodic cellular architectures." Carbon 88: 70-85.

[8] Rezaei, E., S. Haussener, S. Gianella, and A. Ortona. 2016. "Early-stage oxidation behaviour at high temperatures of SiSiC cellular architectures in a porous burner." Ceramics International 42 (14): 16255-16261.

coupled, i.e. the surface temperatures of the metallic plates obtained from the CHT CFD solutions were used as input to the FE analyses. The hot end of the heat exchanger was identified as the most critical one not only because of the thermal loads but also by the temperature dependence of the thermo-physical and thermo-mechanical properties. Under the described conditions, steady-state linear FE thermo-mechanical stress analyses showed that the stresses within the metallic plates were below the rupture limit for the duration of the intended experimental campaign.

Based on the above, the 1st prototype was manufactured and the complete component with insulation was integrated in a laboratory testing rig for assessment of its performance.

Figure 4. Prototype heat exchanger and insulation casing and parts for the covering of the ducts.

2 Experimental testing of prototype

The prototype was integrated in a laboratory scale testing rig to assess its performance under realistic conditions.

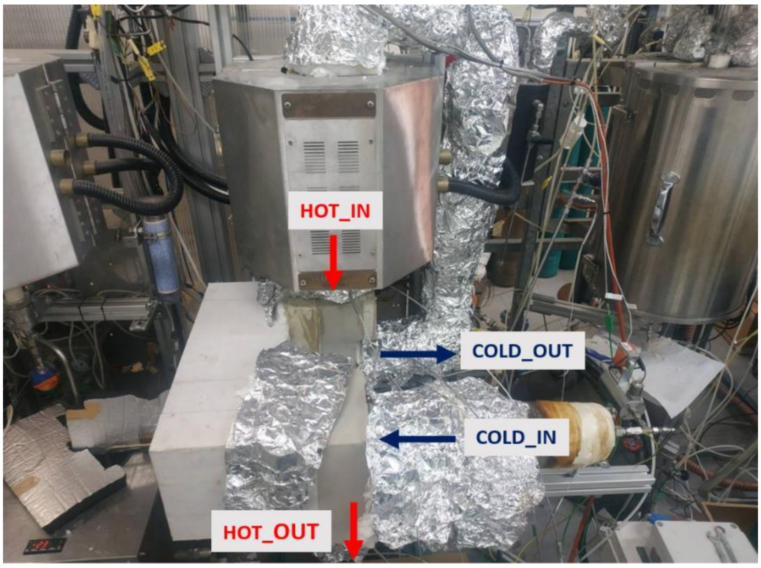

Figure 5. Experimental test rig of the prototype assessment

A total of 21 experiments were performed in order to evaluate the component not only in terms of operational temperatures but also under different thermomechanical loadings. The tests were grouped in three regions: low, medium and high temperature region.

The HHX efficiency was calculated based on the equation:

$$e_c = \frac{T_{cold,out} - T_{cold,in}}{T_{hot,in} - T_{cold,in}}$$

The main conclusions of the experimental evaluation was that the thermal inertia of the unit is too high and needs very long time (several hours) to heat up and reach steady state.

3 Addressing the observed issues

Based on the experimental results additional simulations for the optimization of the HHX design were performed that showed that thermal losses through the ducts and the flanges due to sub-optimal insulation were identified as responsible for the degradation of the component performance.

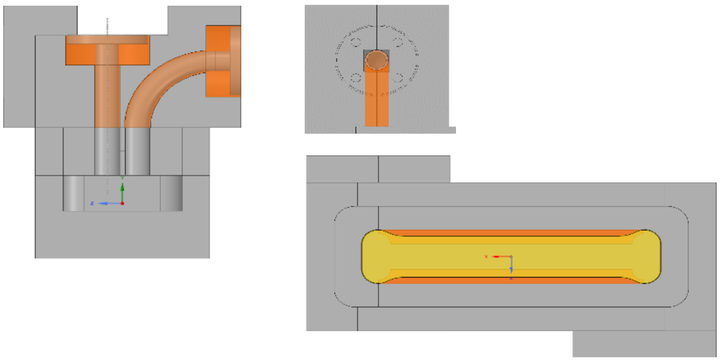

Figure 6. In orange are depicted the gaps between the insulating material and the metal structures and ducts of the small-scale HHX prototype.

As observed in the experiments, the component showed a large thermal inertia which slowed down the heating up phase. The main causes determining such behavior are:

1. The energy input per unit time in the system was not scaled according to the amount of material used for manufacturing the scaled-down HHX (limitations in minimum size of the ceramic cellular inserts determined the height of the channels as well as the material stresses induced by the high temperature), leading to a rather small quantity of power that can quickly heat up the mass of the prototype. In particular, the mass flow rate was small (also due to limitations in the test rig), since the maximum temperatures were already limited by the thermo-mechanical resistance of the metal plates;
2. Flanges and ducts were oversized in comparison to the rest of the component;
3. Thermal losses due to imperfect insulation of flanges.

The results of these simulations suggested the following:

- The inertia of the insulation does not particularly affect the temperature evolution of the cold side during the transient, while the inertia of the HHX plates which link the hot and cold channels is the important one.
- During the transient, the hot fluid gradually heat the plates of the HX until it reaches the same initial temperature of the metal after traveling along the channel, this heat is partially removed by the cold flow which rise its temperature. The HHX seems to perform like a

shorter version of itself. The effective length for which the heat is exchanged with the cold side increases with time.

Based on the experimental and the additional simulation work for the optimization of the HX a new design of the full-scale HHX was proposed. The core optimization was performed with the aim of maximizing the effectiveness while keeping the thermal inertia and the external surface as low as possible.

At the time this report was written a second prototype was being manufactured that will be integrated, within the following months, downstream of the directly heated solar cavity reactor on the HYDROSOL platform at the Plataforma Solar de Almeria in Spain for testing in the actual environment.

History of Changes		
Version	**Publication Date**	**Change**
1.0	30.08.2022	Initial version
1.1	01.11.2022	Revision