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COSMHYC DEMO
INNOVATIVE H2 COMPRESSION

Deliverable 3.6

Public report: H2 compression core components

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1 INTRODUCTION

The COSMHYC DEMO projects aims at developing and demonstrating an innovative compression technology for hydrogen. This technology is a hybrid solution based on the coupling between a Metal Hydride Compressor (MHC) and a Mechanical Compressor (MC). The integration of this solution into a Hydrogen Refueling Station (HRS) enables to combine the high flow rates and flexibility of MC with the reliability and energy efficiency of MHC, enabling an overall cost-efficient solution.

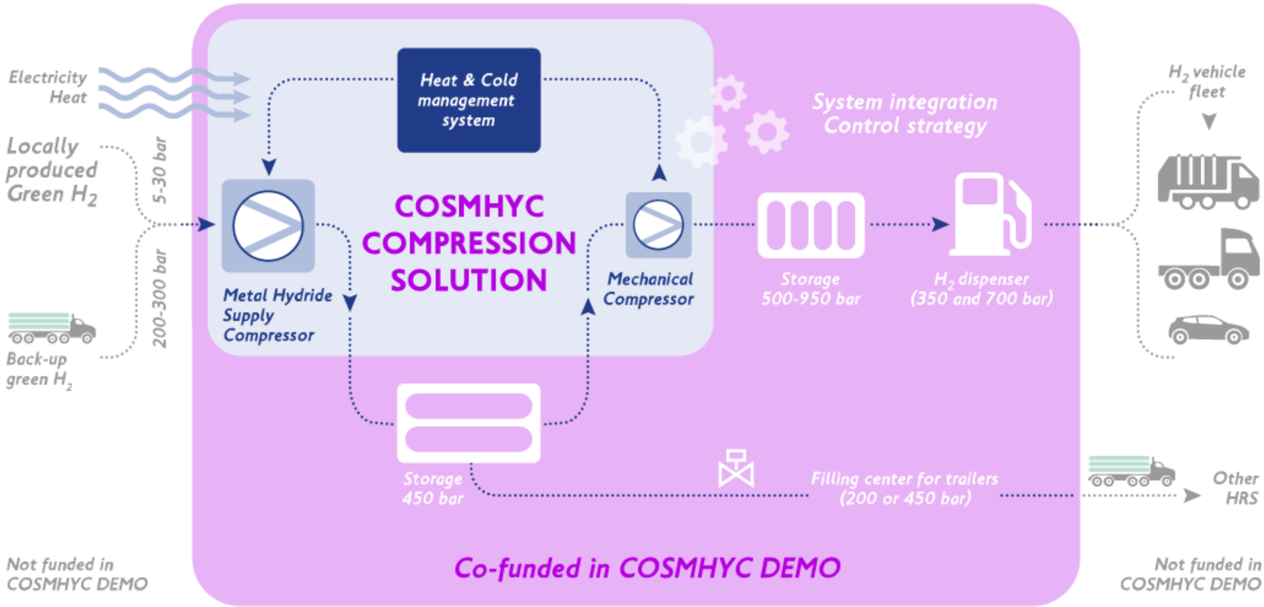

Figure 1- Concept of the COMSHYC DEMO project

The focus of Work Package 3 (WP3) has been to design and manufacture the innovative compression solution prior to implementation into the HRS for the demonstration. For the first time, both compression technologies will be installed on the same site and will be operated together to compress hydrogen from low-pressure (15-30 bar) to very high pressure (950 bar).

To do so, tasks of WP3 have been distributed into 3 actions:

- The selection of 2 suitable metal hydrides for the two first compression stages;
- The design and construction of the metal hydride reactors
- The design and manufacturing of the mechanical compressor

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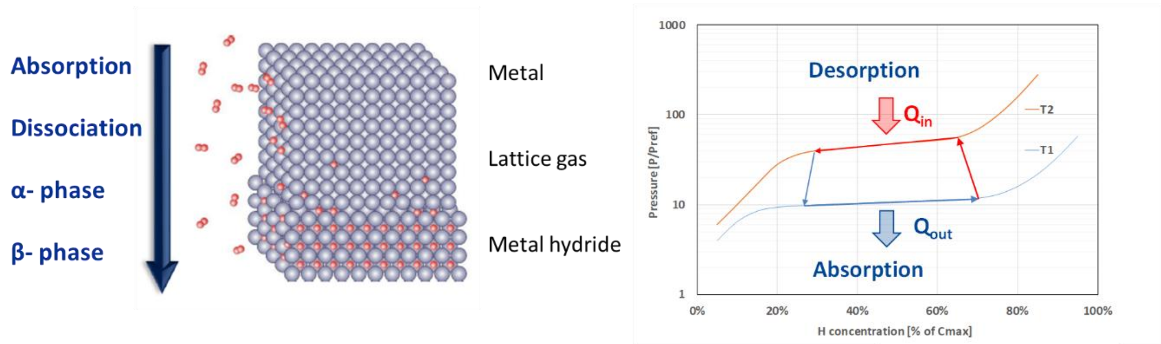
2 SELECTION OF METAL HYDRIDES

2.1 Working principle of metal hydride compression

Metal hydride compression is driven by a chemical process. The main principle of metal hydride compression utilizes a reversible, heat driven interaction between the hydride-forming metal alloy, and hydrogen gas, to form a metal hydride.

Metal hydrides can be selected so that they absorb hydrogen at low temperatures and low pressures, and desorb hydrogen at higher temperatures and pressures. This phenomenon can be used to create a compression effect by absorbing hydrogen at low temperature and pressure, then heating up the hydrides to start desorbing hydrogen at a higher pressure.

The relationship between the temperature of the heat source and the release pressure of the hydrogen in the desorption phase depends on the metal alloy. By combining different metal alloys in different compression stages, it is possible to reach overall pressures of 1000 bar or more. The main challenge for this compression technology is to find the right alloy to optimize the process, by maximizing the amount of hydride absorbed in the metal hydrides while minimizing the energy needed for the whole compression cycle (i.e. absorption, heating, desorption and cooling).



$$M(s) + x/2\ H_2 \xrightleftharpoons[desorption]{absorption} MH_x(s) + Heat$$

Van't Hoff equation: $$\ln P_{eq} = \frac{\Delta H}{RT} - \frac{\Delta S}{R}$$

Figure 2- Working principle of metha hydride compression

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Metal Hydrides are characterized using the PCT (Pressure-Capacity-Temperature) curve. These curves allow, for a given temperature, to know the link between a given capacity and the pressure necessary to reach it.

Usually, there is a plateau on the curve when hydrogen is absorbed/desorbed by the hydride. This area shows the effective part of the absorption/desorption of the hydride, i.e. for a fixed pressure the hydride will absorb/desorb a large part of its maximum capacity. Therefore, having a plateau that is too steep makes the compression less effective.

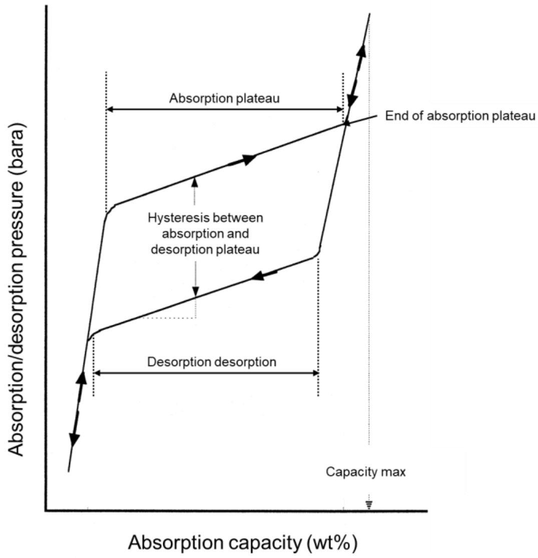

Figure 3 : Diagram of PCT for an hydride

- Case 1: if, for a given temperature, the wanted compression pressure is reached at the top of the “plateau”, then when the hydrogen desorption starts, the pressure will drop quickly and hydrogen cannot be released at the desired pressure.
- Case 2: if the desired pressure is set at the bottom of the "plateau", then there is a risk that, when the temperature is increased to start the desorption phase, the pressure will be much too high, which could be a risk for the whole compression system.

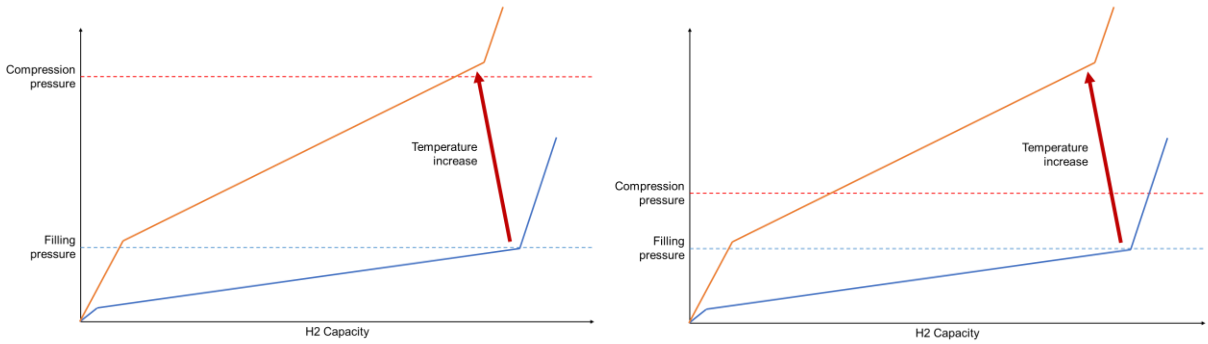

Figure 4 : Diagram of two case with a sloping plateau (case 1: up; Case 2: below)

Both of these cases are not optimal for choosing a hydride that is able to efficiently compress hydrogen. This is why a search in scientific publications allowed us to find a possible solution to improve our known alloys.

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According to a paper published by T. Gamo[1], some alloys have better properties when annealed. The figure below shows these results, highlighting the formation of a plateau by heat treatment at 1100°C for 20 hours.

This annealing operation is a very promising option to improve our hydride, with advantages for more efficient storage and compression. Moreover, the tested compositions are close to the ones we have studied and tested, increasing the chances of success.

Therefore, it seemed interesting to test this solution on our hydrides to see the effects of the heat treatment on the characteristic and compression performance.

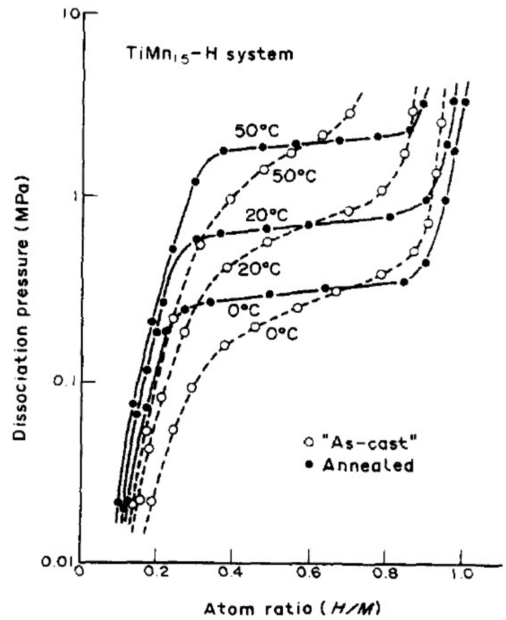

Figure 5 : Effect of annealing on PCT for the AB2 alloy [1]

2.2 Requirement for COSMHYC DEMO

Different metals react differently with hydrogen. Thus, it is crucial to optimally modify the composition of the hydrides, so that these chemical combinations can be used at their best.
Based on previous knowledges from COSMHYC and COMSHYC XL, for which deep investigations had been conducted for identifying and producing rare earth-free metal hydrides, MAHYTEC performed some optimizations to increase the performance and the economic viability of the metal hydrides reactors (without adding any rare earth).
The main requirements are listed below:

- Decrease of the desorption temperature to 120°C (instead of 140/150°C in previous projects) to improve the thermal efficiency and to be able to valorize a higher number of potential waste heat sources;
- Reduce the number of compression stages to 2 (instead of 3 in COSMHYC XL, while having an inlet pressure of 5 to 30 bar (30 bar nominal inlet pressure) and an outlet pressure of 450 bar.

[1] Reference : [1] T. Gamo, Y. Moriwaki, N. Yanagihara et al. Formation and properties of titanium manganese alloy hydrides. J. Hydrogen Energy. 10 (1985) 39-47

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2.3 Annealing treatment

Due to the similarity in the metal hydrides in COSMHYC XL & COSMHYC DEMO, the annealing treatment have been performed on the XL hydrides, to directly observe the performance improvements on them.

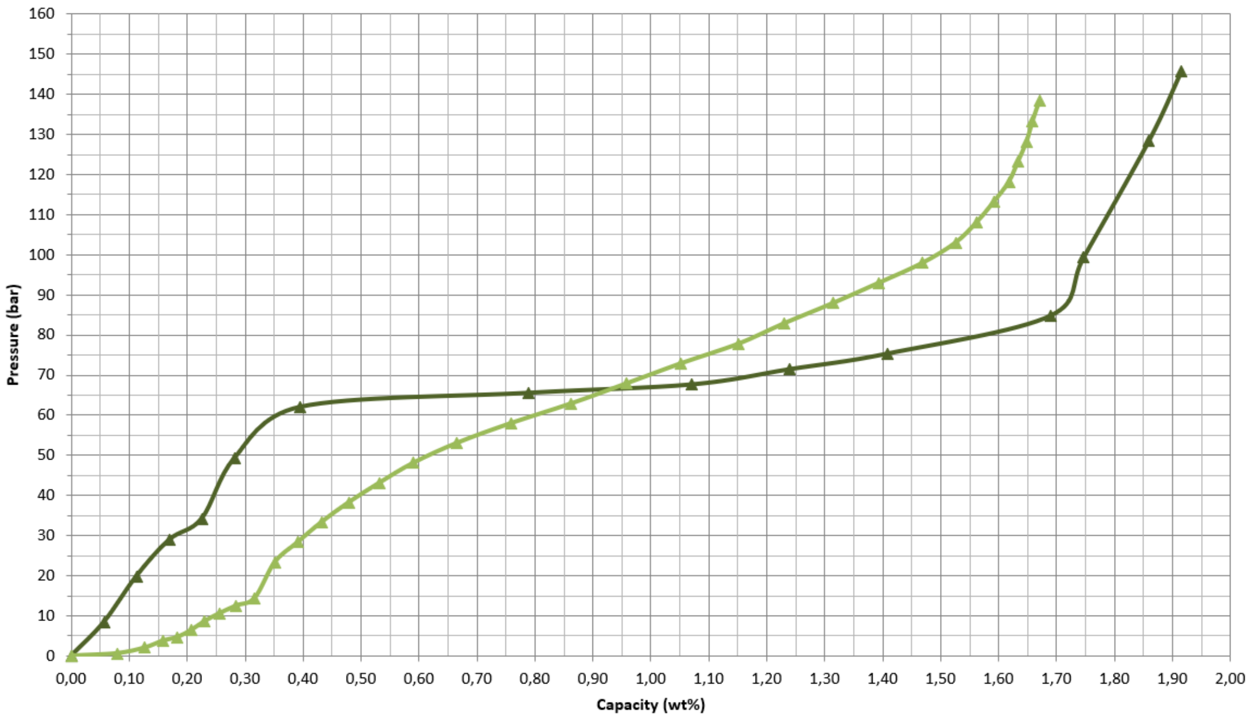

Figure 6- Absorption PCT curves at 22°C of the 3rd stage hydride of COSMHYC XL before (light green) and after (dark green) heat treatment.

Firstly, it can be seen that the hydride has a better capacity to absorb hydrogen. For example, we can see that with a pressure of 100 bar, which is the final pressure of the absorption plateau, the hydride can absorb 1,50 wt% before the heat treatment (light green curve). After treatment (dark green curve), the capacity is 1,75 wt% for the same filling pressure.

Secondly, it can be seen that the plateau has flattened, with the middle of the plateau as the pivot point. So, the left side of the plateau has increased in term of pressure while the left side has decreased. From this modification, it can be deduced that the compression should be more efficient at the end of desorption and would be less efficient at the beginning of desorption.

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2.4 Selection of hydrides

Internal tests performed at MAHYTEC, based on knowledge and experience from the previous COMSHYC projects, enabled to determine the optimal composition and process (incl. heat treatment) for the two compression stages. MAHYTEC has successfully identified different metal alloys with absorption plateaus between 10 and 30 bar for the 1st stage of COSMHYC DEMO and between 90 and 120 bar for the 2nd stage, and desorption pressures between 100 and 150 bar for the 1st stage and between 400 and 450 for the 2nd stage.

The current hydrides studied would be useful in COSMHYC DEMO but compositional optimization would be required to finalize the hydride selection for the 2 compression stages of COSMHYC DEMO, which has equivalent compression stages to the 2nd and 3rd stages of COSMHYC XL but a lower heating temperature from 140°C to 120°C.

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3 DESIGN AND CONSTRUCTION OF THE METAL HYDRIDE REACTORS

The reactors will have 4 main functions:

- Containing the hydrides and allow fast and efficient absorption/desorption;
- Allowing the best heat exchange between hydride and heating fluids in order to reduce the cycling time;
- Resisting the mechanical stress induced by high hydrogen pressure;
- Resisting the temperature variations.

Several heat exchangers have been proposed in previous COSMHYC projects, and have been used and further optimized in collaboration with EIFHYTEC and EIFER. In particular, the manufacturing process of the heat exchanger has been assessed by EIFHYTEC for serial production, which will enable a strong improvement in terms of efficiency and manufacturing costs.

3.1 Design of the shell reactor

The objective of the design of the shell reactor is to optimize some points according to the COSMHYC and COSMHYC XL designs. Particular attention has been paid to the following aspects:

- Shells have to be lighter than previous versions;
- Costs range have to be the same or lower;
- The shell has to be easily dismantlable;
- Shells of the two stages have to be with the same general design in order to improve the industrial costs.

The relevance of using a composite material to achieve these goals has been checked.

3.1.1 Investigation of type II and III tanks

Type II	Type III
Metallic structure and fiber composite wrapped around the cylinder part of the tank to help the metallic structure to withstand the internal pressure. The advantage of this type of tank is that it can have the same metallic structure for both stages and a thickness of fiber depending on the internal pressure.	Metallic liner for the sealing and a fiber composite wrapped around to withstand the internal pressure → the idea is to have the same liner for both stages and a thickness of fiber depending on the internal pressure. The main difficulty of this kind of technology is to keep the dismantlable side of the reactor.

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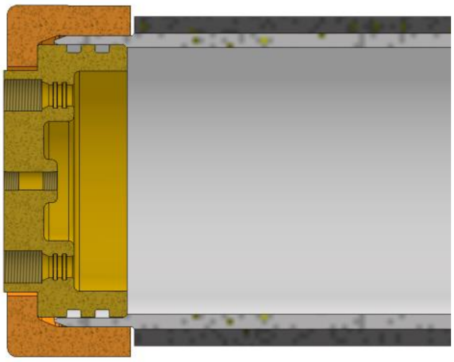

Figure 7: Type II tank

Figure 8: Example of a type III vessel with fiber at both end

These options (Type II & III vessels) have several challenges and therefore, they have not been selected for the project.

3.1.2 Final design

The final design is a type I tank based on the different geometries presented before. It is composed of a shell, two internal caps (one with the thread needed for the inlet and outlet of thermal fluid and hydrogen and the other without any hole) and two external bolts (figure 9).

Figure 9: Final type I tank

The shell is a steel seamless tube in which some machining is done only at both ends to connect the cap and the bolt. Its dimension is a standard and can be adapted to the desired nominal pressure of the tank. Because of the quantity of tank needed in the COSMHYC Demo project, both first and second stage of compressor will have the same dimensions. Indeed, the specificities of the material used (mechanical characteristics, hydrogen compatibility…) require a dedicated manufacturing with a minimum quantity of order. This minimum is not reached with a single stage so both stages will use the design of the second stage. For a more industrial point of view, with bigger quantities of tanks needed, each stage can be optimized to the target pressure in order to save raw material, which means a lighter design and a cheaper final price for a lower pressure.
The cap is a machining part which guarantees the sealing of the end of the tank and allows all the pipe (hydrogen and thermal liquid) to go outside the tank.

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The bolt is a machining part which withstands the bottom effect of the internal pressure. Its external design is a way to optimize the thickness of the shell. Indeed, because of the machining area at both ends, the thickness is smaller in this area but it has to respect a minimum thickness. The external bolt acts as an over-thickness, which allows the use of a thinner shell in the central part on the tank. This design saves millimeters of thickness on the shell, which means a few dozen kilograms less.

3.2 Optimization of the insulation

A big part of the optimization of the COSMHYC and COSMHYC XL reactor is the improvement of the insulation between the heat exchanger and the tank. The better the insulation, the better the energy efficiency of the compressor.

Because of the characteristics of the reactor, the insulation must be inside the tank, between the heat exchanger and the tank. Indeed, the tank is a heavy metallic part with high thermal inertia, so the heat transfers must be restricted to those between the exchanger and the hydride. Each kilowatt transfer to the shell is a lost kilowatt. Therefore, the insulation must resist to the internal pressure in addition to the other constraints that it must meet (no poisoning of the hydride or the hydrogen, temperature range, industrial assembly…).

A literary study allows materials to be classified according to different performance criteria (price, weight, thermal characteristic, see Figure 10 and Figure 11).

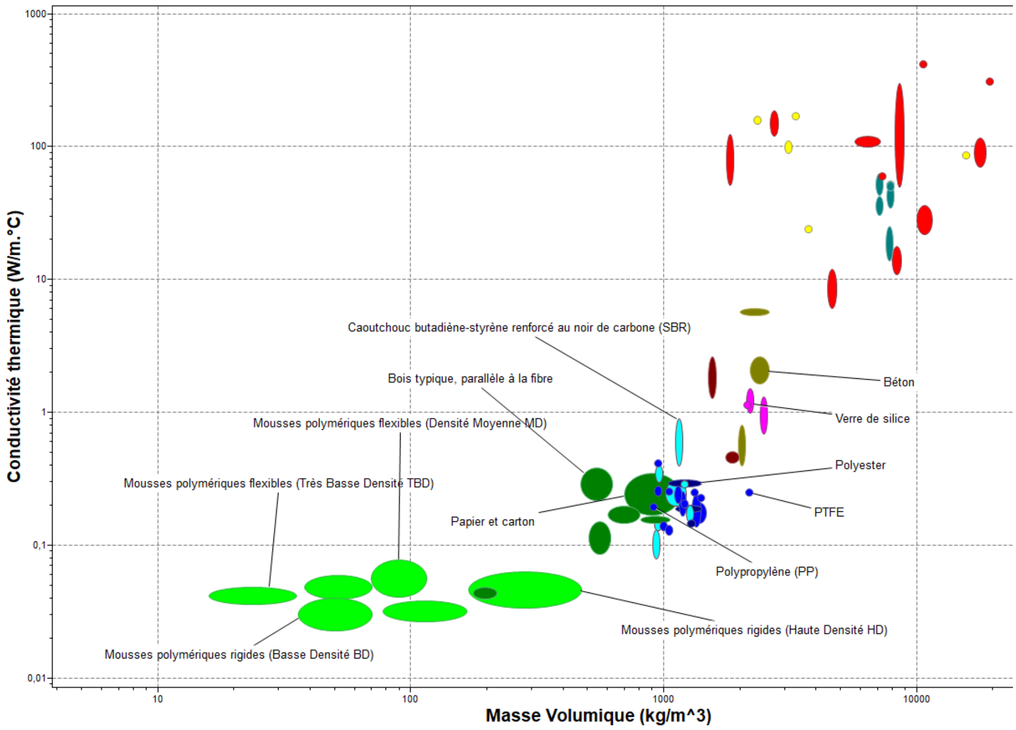

Figure 10: thermal conductivity against weight

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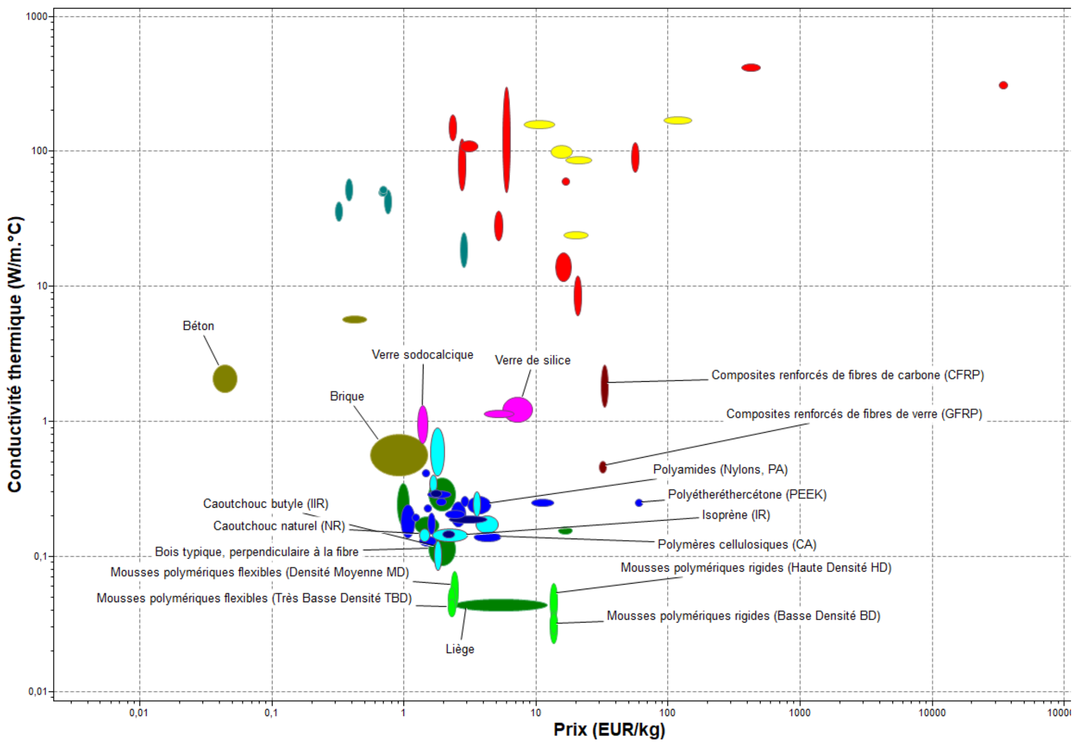

Figure 11: thermal conductivity against price

In order to quantify the effect of each material on the insulation power for the hydride compressor, an experimental study is conducted for several types of insulation materials. The experience consists of a metallic core heated from 15°C to 150°C to simulate the heat exchanger and the hydride. Different materials are wrapped around this core as it would be inside the reactor and the temperature is recorded at different points of the assembly, inside the core, between the core and the insulation part, on the outside surface of the insulation (Figure 12).

Figure 12: Illustration of the experiment (the temperature measurement on the outside of the insulation is protected of the ambient temperature with some rockwool)

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The graph shows the behavior of two different materials, compared to concrete, which is the material used for the tank insulation in the previous COSMHYC projects.

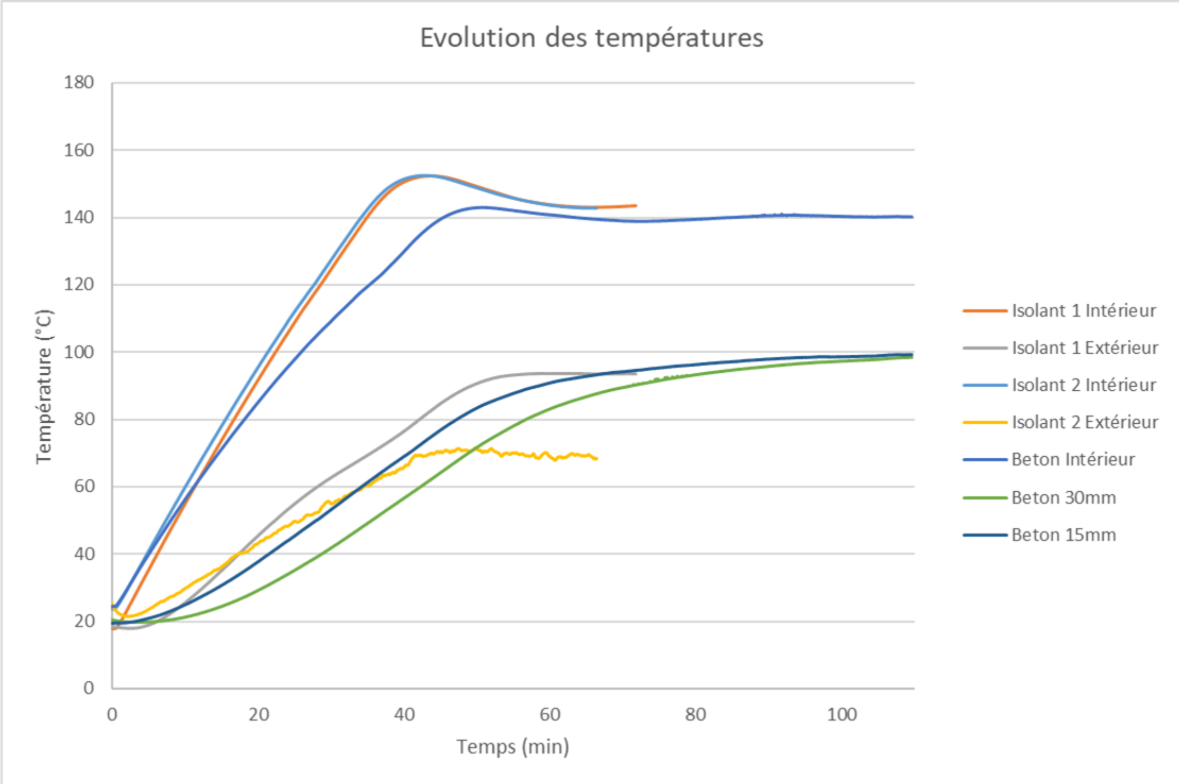

Figure 13: Intermediate conclusion of the insulation optimization

The first comparison that can be made is the different behavior in the internal temperature between concrete and the two other materials (the three curves at the top of the graph). Indeed, the inside temperature with the insulation with concrete take more time to reach 150°C than the two other, and moreover, the stabilized temperature is only 140°C compared to 145°C in the other case, with the same thermal power. This behavior can be explained by the fact that concrete stocks more thermal energy than the other materials, so this can reduce the final efficiency of the reactor.
The other conclusion of these experiment is that the two materials retained are more efficient than concrete at similar thickness.

The final investigations on insulation material leads to the graphic bellow (Figure 14). In order to prevent the effect of the internal temperature and the small delay between the curves of the previous figure, the ratio between internal and external temperatures are plotted. This mean that when the curve is at 1, the internal and external temperatures are the same, and when the ratio is at 0.5, the external temperature is equal to half of the internal temperature.

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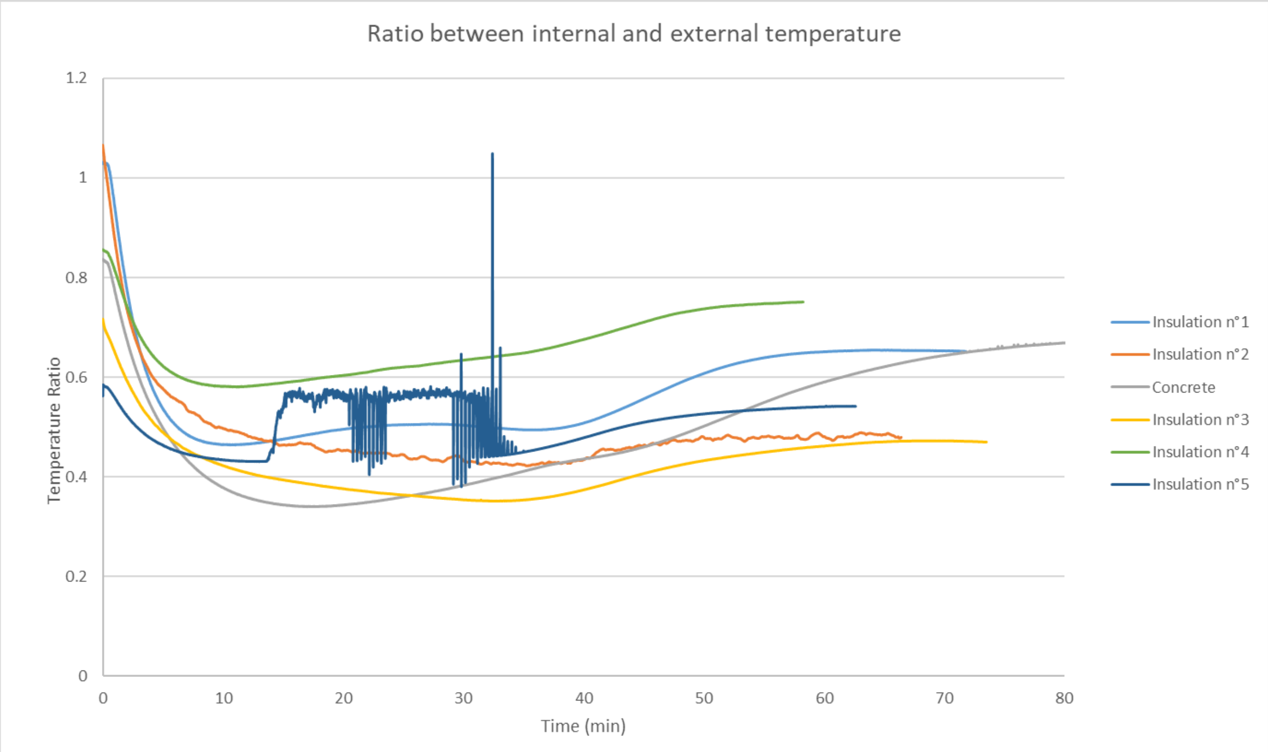

Figure 14: Conclusion of the insulation optimization

Compared to the previous figure, three other insulations are tested. The best choice in term of temperature is the number 3, which reduce more than twice the difference between internal and external temperature. However, this material could contaminate the hydrogen with unwanted impurities, which disqualified it. The second one is the insulation number 2 but with a behavior at high temperature which can degrade its properties.
So, in order to fulfil all the requirements of a good insulation, the material number 5 is chosen. This material is neutral for hydrogen, and its insulation properties are best than concrete, with lighter properties and more industrial for the fabrication.

A final improvement can also be made in the final design: the insulation between the pipe of the heat exchanger and the cap. Indeed, the results of the Cosmhyc experiment show an inhomogeneity of the temperature at the outside of the tank along its length. This means that the temperature is higher next to the cap which is crossed by the thermal pipe and decrease along the tank.
This phenomenon can be explained by the fact that a part of the heat is transferred from the pipe to the cap and next to the shell before going through hydride. This leads to thermal loss.
A way to reduce those loss is to have an insulation between the thermal pipe and the cap. This is not a trivial subject because, among others, this area is a sealing area and has to withstand the pressure so the different part has to be in contact, with material with high mechanical properties, which are not the best characteristics for an optimized insulation. The solution is not found yet but we will investigate this improvement.

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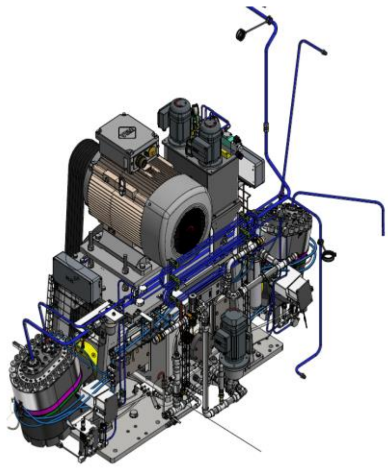
4 DESIGN AND MANUFACTURING OF THE MECHANICAL COMPRESSOR

4.1 Design

Figure below shows the complete mechanical compressor design with dual-heads. The configuration for COSMHYC-DEMO is a 2-stage compressor, including both the 1st stage and 2nd stage compressor heads.

Compressor heads are mounted onto the crank-case in both ends. The crank-case itself is an integral part of the overall crank or compressor frame. Electrical motor, oil system and various BoP are attached to the compressor frame. Overall this provide one equipment skid intended for easy integration into the HRS. Only remaining interface are controls, piping and cooling which are to be integrated with the overall HRS.



Complete Mechanical Compressor design

4.1.1 1st stage head and 2nd stage design optimizations

The 2nd stage head was developed in the former COSMHYC project that ended in 2019 while the 1st stage head was developed in the former COSMHYC-XL project with laboratory tests ended in 2021. Both heads were designed for laboratory prototype tests only and not intended for manufacturing.

A first effort was to redesign the heads now with ease of manufacturing in mind – both with regards to actual manufacturing of each individual component and the assembly hereof. Based on experience redesigning laboratory components into manufacturing ready components, it may impact performance of the components. A first redesign has therefore been thoroughly tested in laboratory to validate reaching of the required performance.

The first redesign lead to various smaller design optimizations that then was tested again. Changes were primarily related to design shapes and clamping of heads, as the design adjustments for manufacturing proved to negatively impact lifetime of the diaphragm.

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4.1.2 Oil system

The oil system prototype was developed in COSMHYC-XL project and was a first for dual-head configuration, whilst at the same time providing flexible and dynamic operation of the compressor.

The prototype components were primarily selected and developed to achieve functionality rather than ease of manufacturing and sourcing. An effort has therefore been conducted on reviewing the entire oil system design, with the aim to replace as many costly components with less costly and more standard ones (easier to source), but without impacting performance. For some components a redesign was required to enable outsourcing of manufacturing to sup-suppliers.

4.1.3 Crank system

The crank system prototype was developed in COSMHYC-XL project and was a first for dual-head configuration. Focus in the design was primarily to place components on the crank in the most straight-forward manner sufficient for laboratory testing.

An effort has therefore been conducted on optimizing the design for manufacturing, in particular ease of assembly of components onto the crank.

Also optimizations have been done on trimming dimensions to ease integration into the HRS module. This also included designing of a sliding skid system that enables easy insertion of the compressor to the HRS during manufacturing. The sliding system also allows for easy replacement of the compressor infield if required.

The sliding system also allows for the compressor to rest onto the HRS module during transport to site, and when installed at site, the compressor is rested onto the very foundation. This ensures that compressor vibrations are transferred to the foundation rather than the HRS module.

4.2 Preparing for manufacturing

When the finalized design was complete for the core compressor components, an exercise where conducted on preparing the components for manufacturing. This primarily covered preparing documentation, processes, safety considerations and assembly guidelines.

This followed an established process within NEL for preparing components for manufacturing and assembly into modules. The aim of this exercise is multiple:

- Ensure sufficient documentation of each component to allow for sourcing at sub-suppliers or own manufacturing
- Component documentation is also needed for the overall HRS safety assessment and third party certification
- Process documentation and assembly guidelines are required to ensure a smooth and time effective process whilst maintaining high quality

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5 CONCLUSION

This report has presented the work performed within WP3 of the COSMHYC Demo project.

The main objectives of WP3 is to design and manufacture the main components of the innovative compression solution to be demonstrated in WP5, by:

- Selecting and producing 2 innovative, rare earth free metal hydrides for the metal hydride compressor (MHC), compressing hydrogen from 5 bar to 450 bar
- Designing & manufacturing efficient metal hydrides reactors, from an energetic and economic point of view, to enable an overall capacity of the metal hydride compressor of 200 kg/day
- Designing & manufacturing the core components of a mechanical compressor (MC) able to compress hydrogen from 450 bar to 950 bar, with the ability to work in degraded mode from 30 bar to 950 bar

A number of areas for improvement have been investigated, for both compression technologies, in order to improve both technical and economic performance (in particular by looking ahead to production on an industrial scale).

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