A conceptual study on the use of a regenerator in a hybrid energy storage unit (LIQHYSMES)

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Abstract. Wind and photovoltaic parks raise the issue of a discontinuous electrical generation. As an energy carrier with high volumetric energy density, liquid hydrogen is an inevitable choice for large-scale energy storage. But, since balancing loads or rapidly evolving fluctuations on the grid with just hydrogen is unrealistic due to its slow response, it is necessary to integrate it with an electrical energy storage device that enables rapid response. This approach combines the use of a liquefaction plant for hydrogen, and a superconducting magnetic energy storage (SMES). Besides, in this case, conventional liquefaction methods are not a viable solution, meaning that a substantial simplification of the process is possible where a regenerator/recuperator is employed and only if temporary/intermediate storage is required. A study is conducted to develop a regenerator (among other parts) for a proof of concept small scale LIQHYSMES system. A 1D model of differential equations is implemented to investigate the regenerator performances, addressing parameters such as regenerator configuration, material and fluid properties, temperature profiles, etc. Results are then analysed and discussed.

1. Introduction

The significant increase of the renewable energy source contribution will eventually increase the need for somehow storing the excess of renewable energy production and for buffering the demands in the electrical grid. Various authors have discussed possible solutions to this issue, as found in [1-4].

In recent works, another approach has been proposed which combines the uses of liquid hydrogen as a high density energy carrier and a superconducting magnetic energy storage (SMES) with the name LIQHYSMES (see [5-10]). This system integrates a liquefaction plant, a tank used to store the liquid hydrogen and a SMES.

The focus of this work will be on a specific part of the liquefaction system, i.e. the regenerator. In general, the use of a regenerator in cryogenic applications is normally restricted to certain particular applications such as Stirling cryocoolers, pulse tubes, and other types of regenerative refrigerators.

2. A generalised mathematical model

2.1. Problem definition

A regenerator is a type of heat exchangers, where the heat is cyclically exchanged between a fluid and a thermal storage material. The analysis of a regenerator is more complex, because of the time and

position dependence of its operating temperatures. To describe the heat transfer process associated with the gas and packaging (where heat is stored temporarily) respectively, an energy balance of a control volume element *dx* is written, which yields to a set of differential equations: one for the fluid and one for the packaging material. The model employed to describe the thermal behaviour of a cryogenics regenerator needs some simplifications in order to be reliable and effective.

2.2. Assumptions

The formulation requires the identification of a one-dimensional control volume of an element *dx* in the packed bed. Several modelling assumptions are made, in order to simplify the analysis of the heat transfer between the fluid and the solid packaging material, and can be summarised as follows:

1. Uniform radial distribution of fluid flow and the packaging material through the regenerator,
2. Heat conduction in the axial direction can be considered negligible if compared with the convective heat transfer,
3. Packed bed of spheres: there is only a point of contact between the spheres, and consequently the axial heat conduction through the layers of the filler material is negligible,
4. It is assumed that there is no heat loss from the walls of the regenerator to the surroundings during the filling/emptying process as well as during the resting time (i.e. the filling/emptying process is fast enough that during this time the heat loss through the wall of the regenerator is negligible),
5. Entrained heat capacity of the fluid is considered negligible, i.e. the change in energy stored within the gas is minor: this is particularly true for gases.

A peculiarity in the functioning of this kind of regenerator lies in the fact that it is impossible to achieve a complete steady state mode, because of its intrinsic unbalances.

2.3. Mathematical model

The regenerator model is a cylinder filled with randomly packed spheres (figure 1-a), and considered divided in small volumes of length *dx* (figure 1-b). Because of the 1-D model, the interaction between the fluid and the bed element in the length *dx*, is simplified as shown in figure 1-c.

For the numerical model an energy balance must be written for each control volume *dx*. If we indicate with: h_F, ρ_F, V_F, $\dot{m}$, the enthalpy, density, volume and mass flow rate of the fluid respectively, and L the length of the regenerator, the energy balance for the gas control volume of length *dx* as per figure 1-c yields to:

$$\alpha A_B (T_B - T_F)\frac{dx}{L} = \dot{m}\frac{\partial h_F}{\partial x}dx + \rho_F V_F \frac{\partial h_F}{\partial t}\frac{dx}{L} \tag{1}$$

The first term on the right hand accounts for the fluid change of enthalpy entering and leaving the control volume. The second term is relative to the energy stored in the fluid (and usually negligible for gas and as previously discussed 5th point) and the last one on the left hand is the rate of heat transfer between the fluid and the bed of spheres. In a similar way an energy balance of the differential element *dx* of the bed of spheres can be expressed as:

$$\alpha A_B (T_F - T_B) = \rho_B c_B V_B \frac{\partial T_B}{\partial t} \tag{2}$$

where ρ_B, c_B and V_B are the density, the specific heat capacity and the total volume of the bed of spheres respectively. As will be discussed later, the properties of hydrogen below about 100K change considerably, i.e. the enthalpy cannot be computed easily as a function only of the temperature T_F, without introducing an unrealistic approximation. For this reason, the equations are solved in an

explicit manner firstly evaluating the enthalpy of the fluid step by step and then converting it to fluid temperature using the program NIST via Matlab.

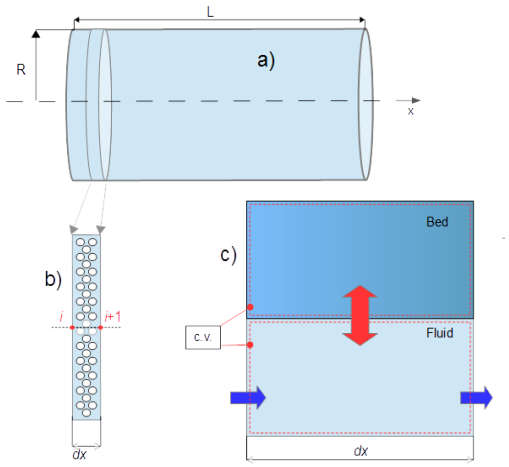

Figure 1. Regenerator model: a)-general dimensions; b)-discretised element with node notation; c)-fluid solid interaction for a *dx* element, with blue arrows indicating the energy transported by the fluid and red arrows indicating the heat transfer occurring.

The discretisation of the governing equations was implemented by means of the finite difference method where the explicit Euler method was used.

The boundary conditions of these equations are:

1. Initially during the first filling, the regenerator itself is at a constant temperature (approximately 21K) throughout its length. Later, the initial temperature profile of the regenerator will come from the final temperature profile of the previous filling or emptying.
2. Inlet temperature of the gaseous hydrogen during the filling process is at a constant value of 80K.
3. The inlet temperature during the emptying process is the constant boiling temperature of hydrogen.

When solving the system of equations, an initial profile of temperature is assigned to the regenerator bed which is supposed not to change during the time interval Δt. Once the new fluid temperature profile is obtained at time t, the new temperature profile of the regenerator bed is calculated at the time step $t+\Delta t$. Of course this method is flawed by stability and accuracy issues if the time and space step are not chosen sufficiently small.

3. Regenerator design and results

The choice of which material to use as thermal accumulator is not trivial, and looking only at the c_p can be misleading. A better approach suggests to compare different materials considering the volumetric heat capacity ($\rho \cdot c_p$) as per figure 2. In the 80K-20K range the best performances pertain to lead (Pb), which achieves the higher heat storage capacity for a given volume, where merely looking only at the c_p would have resulted in PTFE as the better choice. Among various possible correlations for the heat transfer coefficient α, the one available in [11] was used in this work. The regenerator has been designed to completely fill the liquid hydrogen storage tank within 30 minutes. But, the whole regenerator must be pre-cooled to the lowest temperature in order to work properly, and this is reached within 3 hours. Figure 3 shows both the temperature profiles of gaseous hydrogen and the regenerator filling material: the curves represent the temperature profiles at specific time steps during the cooling of the regenerator and illustrate the decrease of the temperature of the filling material while is cooled by the gas.

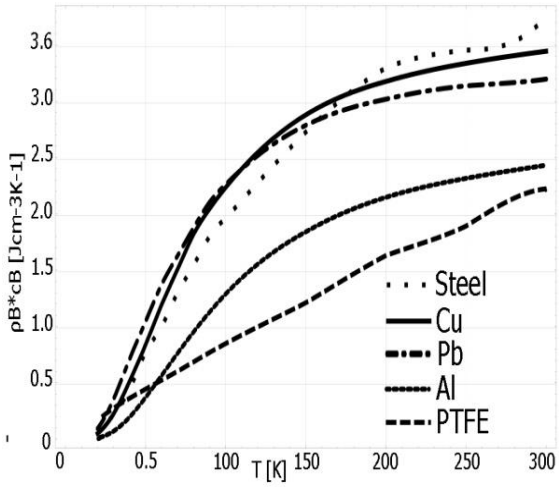

Figure 2. Volumetric heat capacity versus temperature, for different materials.

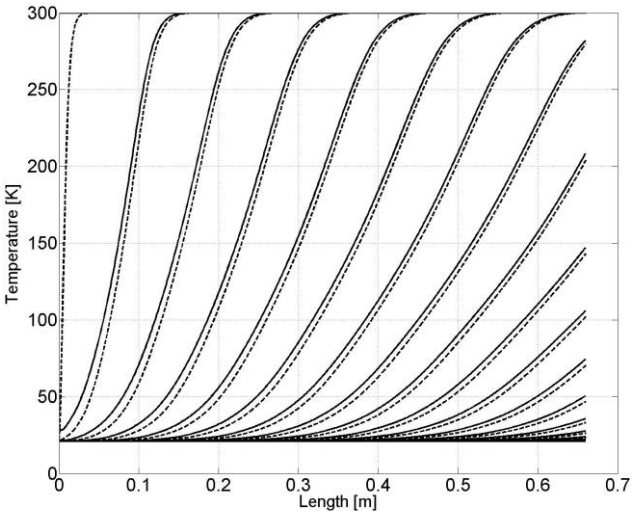

Figure 3. First cooling of the regenerator: full line - temperature of the regenerator; dash line - temperature of the gaseous hydrogen.

The temperature difference between the regenerator bed and the gas at each space/time step is very small and within the validity of the assumption for the Biot number. The process is interrupted once the constant temperature along the regenerator length is achieved.

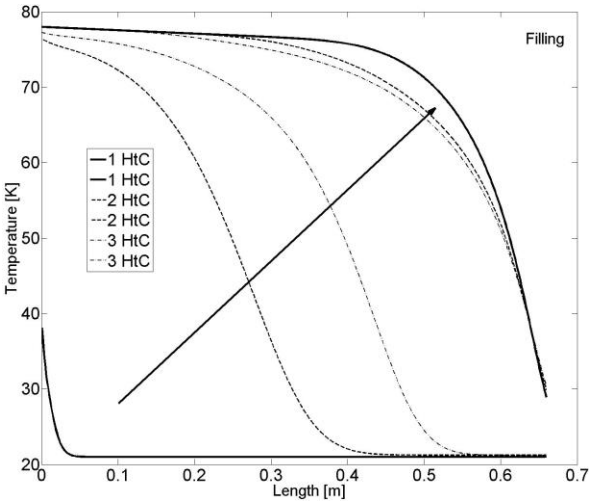

Figure 4. Evolution from the initial to the final regenerator temperature profiles (arrow direction), for 3 filling processes at a maximum pressure of 10 MPa.

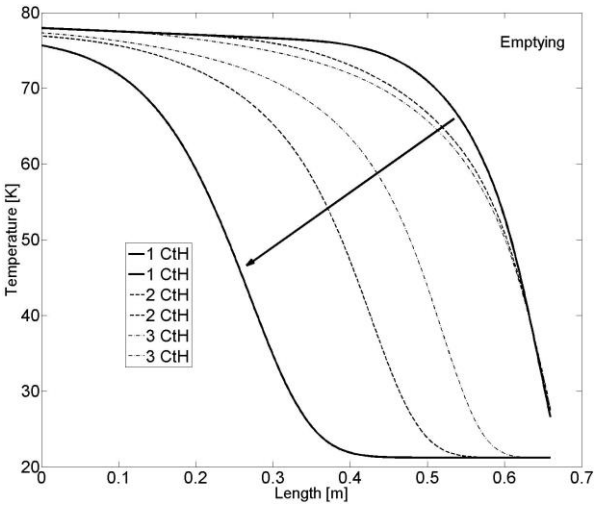

Figure 5. Evolution from the initial to the final regenerator temperature profiles (arrow direction), for 3 emptying processes at 0.14 MPa.

The simulation results of 3 complete cycles of filling and emptying, after achieving independence of the results from the grid and the time step, are shown in figure 4 and figure 5, where the variation of the temperature profiles within the regenerator packing is illustrated. Each simulation stopped after, either the exiting temperature of the gas exceeded 32K (during filling), or the stored liquid hydrogen was completely consumed. From figure 4 to 7, only 2 profiles are plotted for each stage, the initial one and the last one and the arrow indicate the direction on how to read the plot. The influence of the pressure of the entering gas on the regenerator thermal behaviour is presented in figures 6 and 7. The

emptying pressure always remains the same, for both cases. These plots suggest that at higher pressure, the energy transferred within the packaging and the gas for each full cycle (filling + emptying), is considerably more than at low pressure, and allows a longer duration between 2 regenerations. What is the draw back in the use of a regenerator at these low temperatures? It is important to point out that the regenerator cannot achieve steady cyclic behaviour.

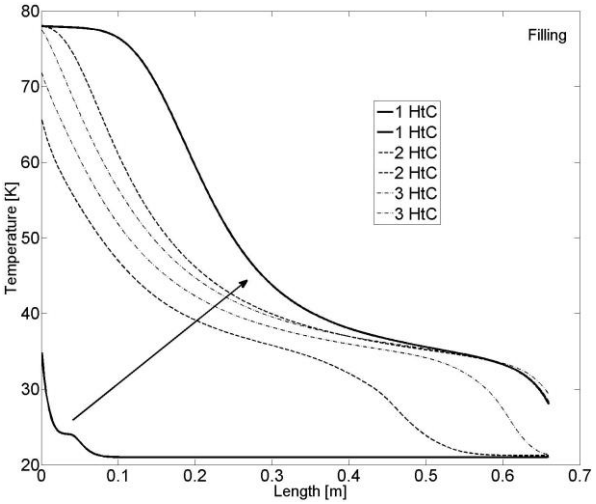

Figure 6. Evolution from the initial to the final regenerator temperature profiles (arrow direction), for 3 filling processes at a maximum pressure of 1.4 MPa.

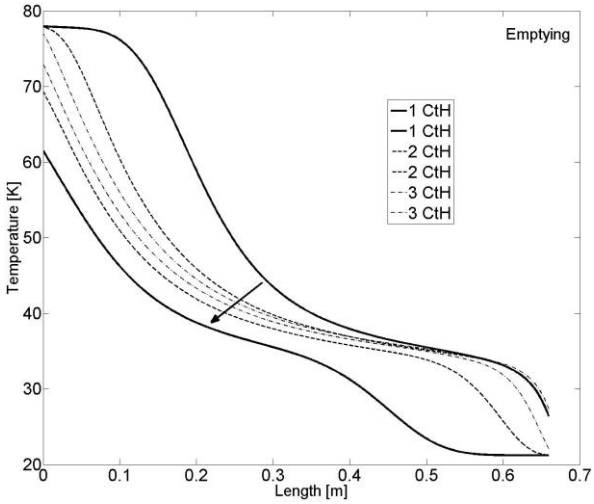

Figure 7. Evolution from the initial to the final regenerator temperature profiles (arrow direction), for 3 emptying processes at 0.14 MPa.

After each cycle there is a continuous degradation of the regenerator heating storage capacity. Figures 8 and 9 address this problem.

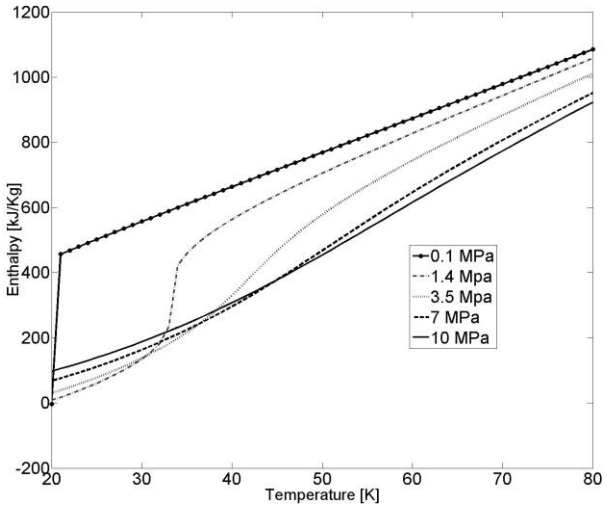

Figure 8. Temperature versus enthalpy for hydrogen at various pressures ranging from 0.1 MPa up to 10 MPa.

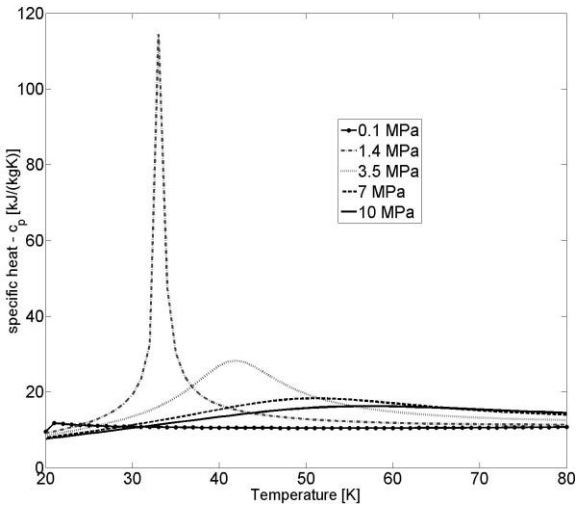

Figure 9. Temperature versus specific heat for hydrogen at various pressures ranging from 0.1 MPa up to 10 MPa.

Except for normal heat dissipation across the wall of the regenerator (and of course, the cryostat), there is an unavoidable deterioration of the energy: in figure 8 the temperature versus enthalpy is plotted for pressure between 0.1 MPa and 10 MPa and it highlights the slope change of enthalpy

depending on the pressure. Above the critical temperature, the rise in the temperature is directly correlated with the peak of the specific heat capacity and the rapid increase of enthalpy and 0.1 MPa is due to the heat of vaporisation. A quick look gives an idea of the amount of energy that cannot be recovered during the emptying process: for instance, referring to figure 8, if we consider a variation of enthalpy-Δh1 (T=60K, T=40K at p=40bar)= 412kJ/kg and Δh2 (T=60K, T=40K at p=1bar)= 210kJ/kg, it is clear that being the cooling capacity of the hydrogen during the emptying of the tank (i.e. Δh2) lower than in the case of the filling of the tank (i.e. Δh1), there is a net loss of regeneration capacity of about half, meaning that after some cycles the regenerator must be re-cooled (or regenerated) relatively often. After establishing the importance of the pressure on the regenerator performances, it is of interest to plot the actual mass of liquid hydrogen obtained after each filling process at different pressures. In figure 10, the increase of the liquefied mass is as expected, but interestingly it is exposed that at high pressure, the increase in the mass flattens thus showing a possible lack of convenience in increasing the working pressure excessively.

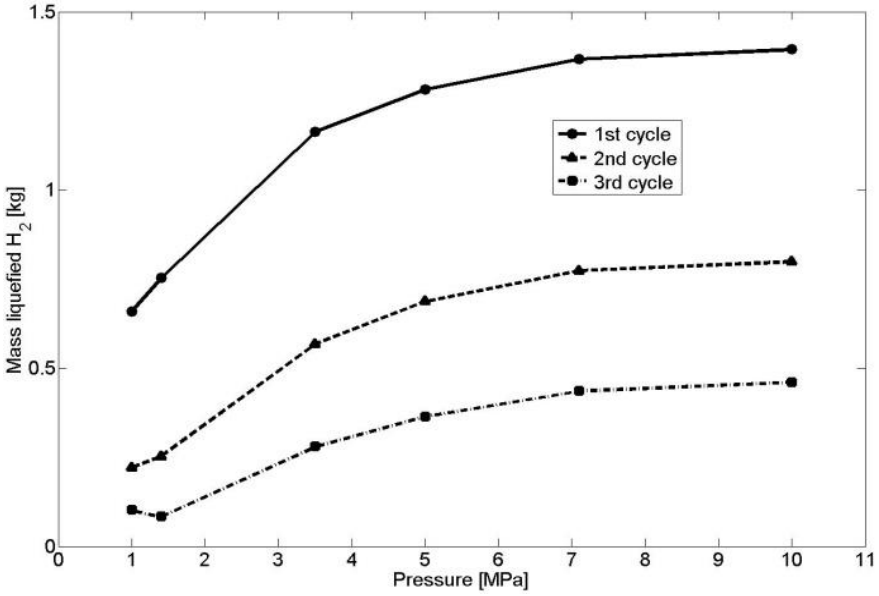

Figure 10. Mass of liquefied hydrogen at different pressures.

4. Overview on the LIQHYSMES design

After having defined the thermal characteristics of the regenerator, it was possible to develop a complete layout for the LIQHYSMES arrangement as well as an introduction of the working mechanism.

Figure 11 gives a general overview of the current design of the whole system, where all the components are shown.

Ideally, the process results in the following path: from the high pressure tank (approximately 200bar), gaseous hydrogen is sent into a liquid nitrogen heat exchanger at around 35bar, where the temperature of the working fluid (i.e. H_2) is decreased from room temperature to 80K. After that, the pipe brings the cooled H_2 into the cryostat where it passes through the regenerator (earlier pre-cooled down to about 21K) and further on is throttled in a Joule-Thompson valve: the liquefied H_2 goes directly above the SMES in order to keep it completely covered with liquid hydrogen, and the excess which is not necessary to keep the magnet cold is stored in a separate tank. The non-liquefied part of H_2 is evacuated in a pipe that goes directly inside the regenerator, to reuse the enthalpy of the cold gas to partially compensate the losses in the regenerator. Ideally, the process results in the following path: from the high pressure tank (approximately 200bar), gaseous hydrogen is sent into a liquid nitrogen

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Once the capacity of the liquid H_2 tank has been reached, the whole process is stopped. The pressure at which liquid hydrogen is stored is around 1.1bar. When a request in the grid is issued, the system reacts initially discharging the energy stored in the magnet, and simultaneously liquid hydrogen is re-gasified and made available at the outlet of the cryostat for use either in gas turbines or fuel cells. The hydrogen warming up takes some time and during this time the SMES will cover the request from the grid. The discharge of hydrogen can be obtained in two ways: increasing the internal pressure forcing the liquid into the regenerator, or evaporating the liquid H_2 by means of a heater. The latter method, of course, does not allow partial use of the liquid enthalpy to increase the cooling effect in the regenerator.

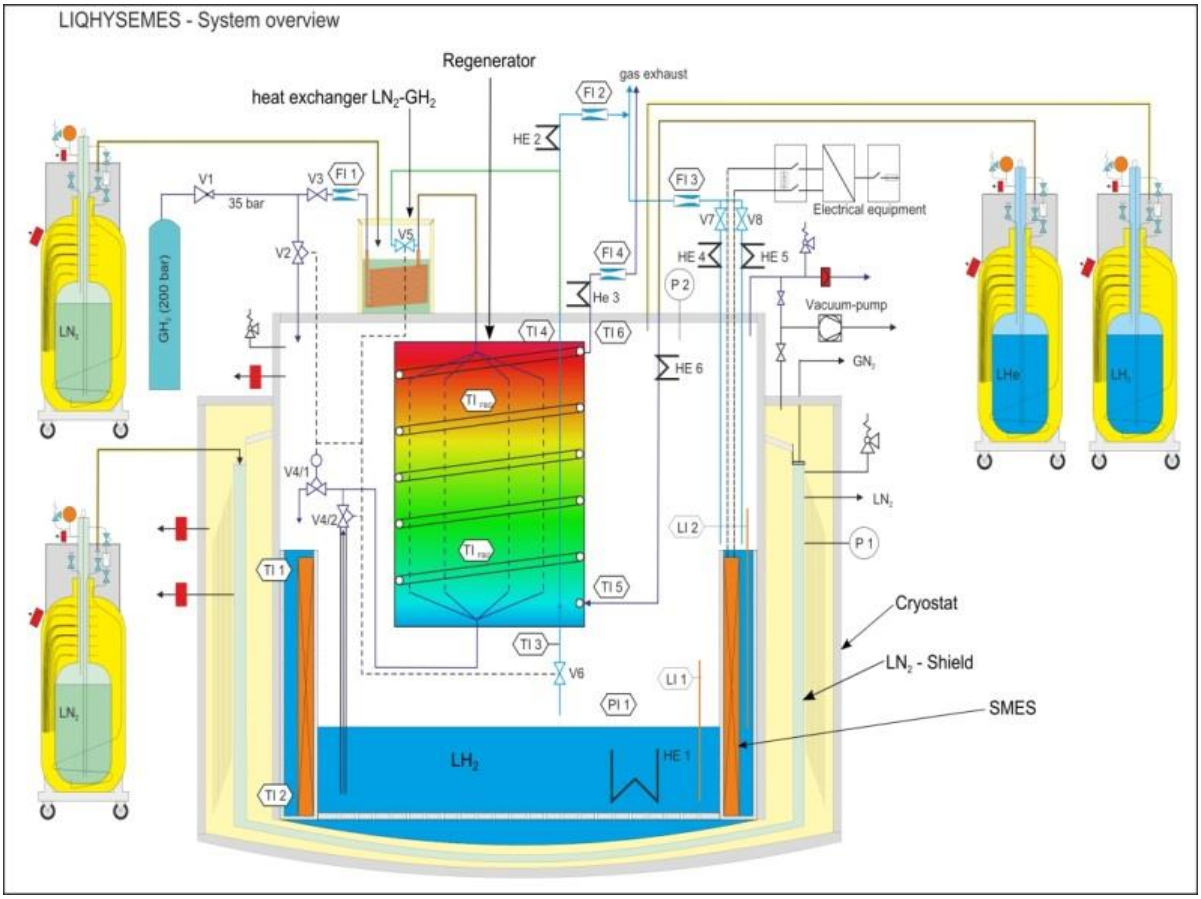

Figure 11. Schematic illustration of all the components for this proof of concept.

The regenerator is a simple device that allows the accumulation of heat. A principal characteristic is not to operate continuously but periodically, storing heat in a packing during the filling process and giving up the stored heat in the emptying phase. Typically it consists in a column filled with a material with a good heat capacity, through which the gas flows. It is worth to mention that the ortho-para

conversion of hydrogen is not considered as an issue in this proof-of-concept system, as the resting time of liquid hydrogen within the tank is estimated to be less than a day. In case of longer storage, a catalytic converter should be employed, for instance in the regenerator or in a heat exchanger.

5. Conclusions and future work

Following the characteristics obtained for the regenerator, it was possible to develop a complete layout for the LIQHYSMES arrangement. The components are almost all manufactured, and it will be built and tested shortly. The pre-calculations/simulations have highlighted issues which are normally not taken in consideration for standard regenerator design, in particular, it is clear that the regenerator needs a complete re-cooling after a few cycles, and not only because of the natural occurring heat loads insisting on the outside of the cryostat, but mainly because of the net loss in heat storage capabilities of the regenerator bed, after each cycle. This is due to the different slope in the enthalpy variation at very different pressures, though suggesting that storing the liquid hydrogen at a higher pressure could reduce the numbers of re-cooling. Another interesting point in the use of hydrogen lies in the fact that even though a certain evaporation rate of the liquid bath is unavoidable, this mass is not wasted but can be used for instance in a fuel cell and so the energy obtained can be used to run auxiliary systems.

Future steps require the investigation of an “optimum” in terms of working pressure, for the gas during the hot-to-cold blow, during the cold-to-hot blow and for the storage of liquid hydrogen.

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