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Efficient Large Scale Hydrogen Liquefaction

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Abstract

A broad acceptance of hydrogen as an alternative energy carrier requires cost-efficient production, transport and storage solutions. Liquid hydrogen can play an important role in these scenarios. But it is a necessity that the hydrogen liquefaction is performed in a very efficient way. The best liquefaction plants in operation today, have a power requirement of about 11 kWh/kg of liquid hydrogen. Several partners from industry and research institutes are presently working together in the IDEALHY project and are developing the conceptual design of a large capacity hydrogen liquefaction plant, which has a power consumption lower than 7 kWh/kg. In the paper the method of identification of the most promising liquefaction process will be described. The search for suitable components for a plant with a capacity of 50 t/d is under way and first results of this investigation will be reported.

Introduction

Hydrogen is seen as a promising future energy carrier. It provides energy in a clean way with nearly no pollution at the point of use. In order to make it useable for customers at great distances of a hydrogen infrastructure, transportation and storage is necessary. Because of its high density hydrogen in liquid state is often identified as the most favorable option. The liquefaction process needs to be efficient in order to make this option reasonable from an economic and ecological point of view.

1. Finding the liquefaction cycle

The IDEALHY Project has been started to identify a process that liquefies hydrogen more efficiently than any other existing cycle is able to. IDEALHY not only tries to find out the most efficient liquefaction cycle and the necessary components, but also deals with the whole concept for building such a plant. IDEALHY is an EU funded project that focuses on very large scale liquefaction facilities with a capacity of 50 t/d or above.

In order to reduce the power consumption for hydrogen liquefaction it is necessary to find out, where most of the power in a given process is consumed, whether the respective amount of energy can be reduced and how this can be done. Possible ways to reduce energy consumptions are to use different or improved components as well as changing the process itself.

The first step was to analyze already existing liquefaction concepts described in literature and to compare these regarding their exergy consumption, their investment costs and their compactness. A difficulty for the comparison of published liquefaction cycles is that they refer to different boundary conditions and component efficiencies. In order to get meaningful results it was necessary to calculate all processes with identical boundary conditions such as feed and output parameters. The chosen boundary conditions have been published earlier [1].

A very important parameter is the pressure of the hydrogen, which is being liquefied. As boundary condition a feed pressure of 20 bar is assumed, which is common for pressure swing adsorption.

The comparison of the cycles showed that it is of advantage to compress the feed to a somewhat higher pressure, because that makes the cooling below 80 K much simpler. This can be understood by inspection of the specific heat of hydrogen at different pressures (Fig. 1).

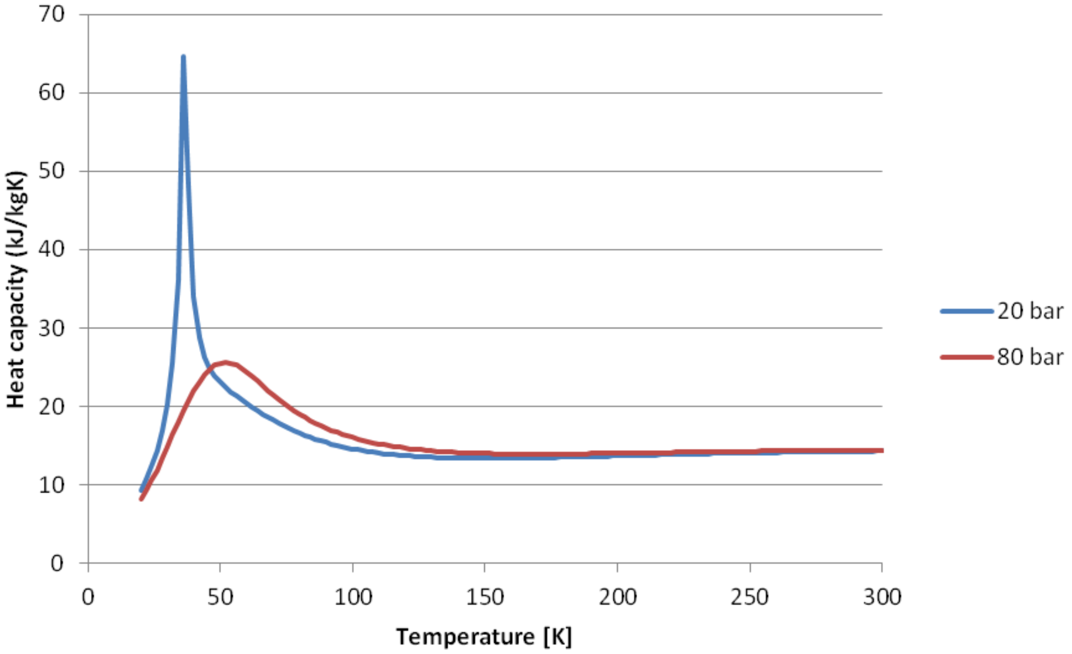

Figure 1: Heat capacity of equilibrium hydrogen at 20 bar and at 80 bar [4].

For the IDEALHY process a compression of the feed to the 80 bar level was chosen.

To identify an efficient, but also realistic process a number of iteration loops are necessary. Figure 2 shows an early version of the IDEALHY cycle.

The pre-cooling will be carried out with the help of a mixed refrigerant cycle. Presently existing large scale liquefaction plants use liquid nitrogen for precooling purposes, fixing this cooling level to 80 K. Aiming for an efficient large scale hydrogen liquefaction, pre-cooling with liquid nitrogen is not a good solution, since it is highly inefficient, when the production of liquid nitrogen is taken into account. Alternatively one could integrate a closed nitrogen expander cycle into the liquefaction process, which already improves the efficiency slightly. Other options for pre-cooling are additional high temperature expansion stages within the helium Brayton cycle to provide cooling. This turns out to be difficult since compressing light gases is complicated and power consuming. Considering all mentioned pre-cooling concepts, the concept of a mixed refrigerant cycle seems to be the most promising solution. It is already common technology in the field of liquefying natural gas (LNG). The advantage is the possibility to provide gliding temperatures throughout condensation and evaporation of the refrigerant blend and that way to optimize the refrigerant mixture to adjust the evaporation curve to the process.

Components of the mixed refrigerant are nitrogen, methane, ethylene, ethane, propene, n-butane, and n-pentane. The composition must be adapted to the needed temperature glide.

The next stage of cooling is performed by two Brayton cycles with a total of 5 expanders, whose power is transferred to directly coupled one-stage turbo-compressors, which operate at ambient temperature.
The brake compressors are working in series, whereas the expanders are working partially in parallel. This arrangement is due to the enthalpy drop in the expanders and enthalpy

increase in the compressors, thus promising to be the best possible working condition concerning the operation of both, expanders and compressors.

A flash gas cycle from the wet expander is planned to recycle the flash gas that arises from the final hydrogen liquefaction stage. Expansion machines have been chosen instead of throttle valves because of a lower vapor fraction can be achieved.

The ortho- to para-hydrogen conversion is performed in an adiabatic converter at 80 K and continuous conversion inside the heat exchangers below approximately 80 K. 98 % para content has been chosen to be the para-hydrogen content in the product.

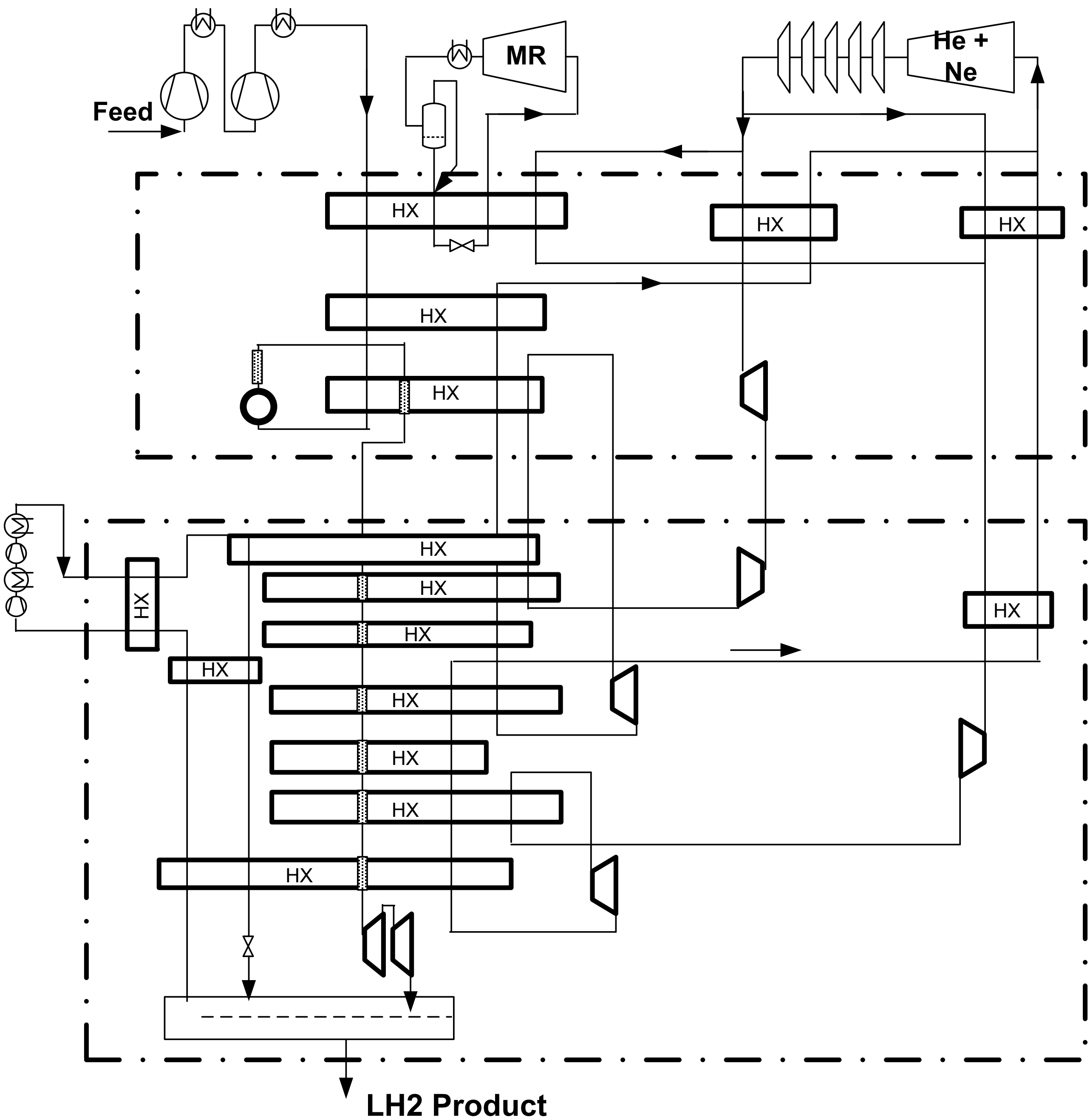

Figure 2: Flow diagram of an early IDEALHY process. (HX – heat exchanger, LH2 – liquid hydrogen, MR – mixed refrigerant, shaded areas represent ortho-para-catalyst)

A real challenge was the choice of the refrigerant for the Brayton cycles. Helium, Neon, Hydrogen and mixtures of these gases are possible refrigerants. Neon has the disadvantage of the need to control, that no liquid is produced at the expander outlet. Hydrogen is not compatible with all bearing materials. Helium is the preferred refrigerant because of its heat transfer characteristics, which result in lower pressure drop and a better heat transfer coefficient. But because of the low molecular weight of helium there are no turbo compressors available yet being able to provide the needed maximum circumferential speed of the blades. Therefore a mixture of helium and neon has been proposed in this work as favorable working fluid. This improves the situation on the molecular weight problem, but also limits the minimum cooling temperature because of the triple point of neon at 24.6 K. The exact ratio of these two gases is still being evaluated but will be close to a molar ratio of approximately 3:1.

Besides the chosen refrigerant and boundary conditions the power consumption also depends on the components and their respective efficiencies. To find the best and realistic solutions for heat exchangers, compressors and expanders, a close cooperation with respective manufacturers is crucial. This iterative process is currently underway. Since the turbo compressors use the largest input power of the process, they need to be designed quite carefully.

Several iteration steps were performed with variation of refrigerant composition, pressure levels and partial pre-cooling by a chiller. In the end the solution shown in Figure 3 was chosen: Two helium/neon streams enter the turbo compressor, one at elevated pressure. This decreases the volumetric flow rate of the lower stage and increases the volumetric flow rate in the upper stage. The brake compressors are not working in series anymore and the helium/neon stream is divided at the compressor outlet.

The two high pressure streams, which enter the coldbox are cooled by a chiller to about 6 °C. This reduces the load and the pressure drop in the cryogenic heat exchangers and reduces the suction temperature of the lower stages of the main turbo compressor.

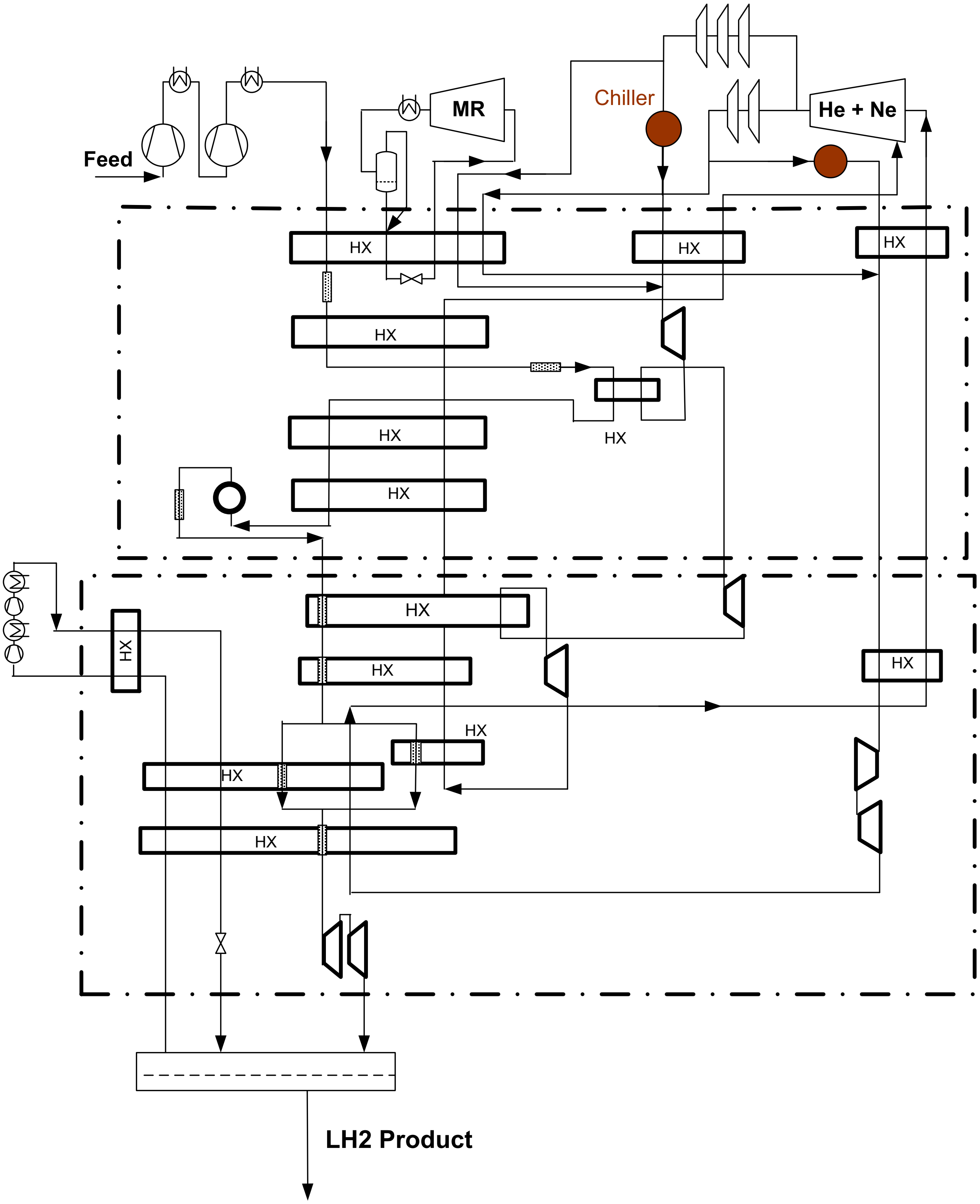

Figure 3: Modified flow diagram of the IDEALHY process taking into account cycle compressor characteristics.

Because helium and neon are both rather expensive gases, a hermetic system of the cycle is necessary that eliminates leakage. So for both the main compressor as well as the turbine/compressors hermetic machines with active magnetic bearings and integrated electric motors are proposed.

2. Conclusions

The paper presents steps to develop a high efficiency plant for large scale hydrogen liquefaction. The comparison and analysis of already existing liquefaction cycles led to a first version of a large scale liquefaction process. This included a feed pressure of 20 bar and a following compression of it up to 80 bar. The pre-cooling is carried out via a mixed refrigerant cycle followed by two Brayton cycles with a helium/neon mixture as refrigerant. The initial goal of a specific power consumption of below 7 kWh/kg has been reached.

3. Acknowledgement

The research leading to the results presented in this paper has received funding from the European Union's Seventh Framework Program (FP7/2007-2013) for the Fuel Cells and Hydrogen Joint Technology Initiative under grand agreement N° [278177].

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