Mixed refrigerant cycle with neon, hydrogen, and helium for cooling sc power transmission lines

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Abstract. The use of superconductors in very long power transmission lines requires a reliable and effective cooling. Since the use of cryocoolers does not appear feasible for very long distances, a cryogenic refrigeration cycle needs to be developed. For cooling superconducting cables based on MgB$_2$ ($T_c = 39$ K), liquid hydrogen (LH$_2$) is the obvious cooling agent. For recooling LH$_2$, one would need a refrigeration cycle providing temperatures at around 20 K. For this purpose, one could propose the use of a helium refrigeration cycle. But the very low molecular weight of helium restricts the use of turbo compressors, which limits the overall efficiency. In order to increase the molecular weight of the refrigerant a mixture of cryogens could be used, allowing the use of a turbo compressor. Temperatures below the triple point of neon are achieved by phase separation. This paper presents a possible layout of a refrigeration cycle utilizing a three component mixture of neon, hydrogen, and helium.

1. Introduction
In recent years, several publications suggested the integration of superconducting MgB$_2$ power transmission lines cooled by liquid hydrogen (LH$_2$) or gaseous helium (GHe) at 20 K into the grid [1–4, 6–8]. The simultaneous transfer of electrical and chemical energy seems advantageous if LH$_2$ is demanded at one end of the transmission line, too. Such a concept is called a hybrid transfer line. The concept of superconducting cables based on high temperature superconductors (HTS) cooled by hydrogen [4] or nitrogen ( [12] and [13]) has been already proven successfully in demonstrators and even industrial applications [11]. But the longest cable project so far is only 1 km long, which is far less than the proposed length of several hundred kilometers. Due to remaining heat leaks into the sc cable and the heat input caused by circulation pumps, recooling units in discrete distances seem unavoidable for long distance applications, whether the line is cooled by LH$_2$ or GHe. The latter option will result in lower capacities because of poorer insulation properties of GHe. The concrete distance between such stations depends mainly on the overall heat leak to the system and the pressure drop within the cooling channels. Most concepts refer to a multiple walled cryogenic envelope with the sc cable being cooled by the cooling agent in the innermost envelope. An additional thermal shield with liquid nitrogen (LN$_2$) reduces the heat load to the sc cable envelope significantly. Regardless of the cooling machine’s working principle, such recooling plants need to operate very cost efficient and at high availability levels to provide a reliable power transmission path. Actual sc cable demonstrators are utilizing the concepts of lost boiling of LN$_2$ (see [11]) or cryocoolers (see [4, 12, 13]) to compensate the heat load. These have proven to be sufficient for the demonstrators. But it seems doubtful that these concepts are sufficient for a sc transmission
line of several hundred kilometers length. The specific costs of a cryocooler referring to its cooling capacity are rather high and range between 0.8 to 4 \$/kW\(^{-1}\) at an operating temperature of 20 K. At this temperature range the cooler efficiency ranges between 2 and 12 % of Carnot [9]. Furthermore, cryocoolers suffer from continuously wear, steadily decreasing the available cooling power [14]. Cryocoolers are most suitable in the cooling power range between 10 and 100 W since there exists no cost efficient Claude cycle refrigerator [9]. In contradiction to this, Brayton or Claude cycles can provide cooling power of several kilowatts at higher efficiencies (around 17 % of Carnot). Commercially available cable cryostats feature a remaining heat leak of 1 kW km\(^{-1}\) [6], which results in a demanded refrigeration capacity of 30 kW per cooling unit if a distance of 30 km is assumed. A Turbo Brayton cycle might provide an overall efficiency of 25 % of Carnot [10], since centrifugal compressors are characterized by an isothermal compression efficiency of 70 % compared to 55 % for conventional screw compressors. Furthermore, the compression chamber is completely free of oil which reduces the installation effort if no sophisticated oil removal system is required. But turbo compressors are rather disadvantageous in the handling of light weight gases such as hydrogen and helium. The achievable pressure ratios per stage are very low for these gases, so that the compressors require multiple stages and high capital costs.

This paper presents a conceptual approach to establish an efficient cryogenic refrigeration cycle based on a three component mixed refrigerant. The addition of heavier neon reduces the number of stages, whereas hydrogen can help to subsequently remove the neon before temperatures below 25 K are reached.

2. Operating parameters of the cooling agent
To cool a sc cable made of MgB\(_2\), LH\(_2\) and GHe could be considered in general. In both cases the maximum operating temperature is set to be 25 K to achieve reasonable critical currents with MgB\(_2\). If LH\(_2\) is supposed to be the cooling agent, the operating parameters are defined by its thermophysical properties, too. In general, sc cable conduits shall be operated either within the liquid or the gaseous phase of the cooling agent. In case of LH\(_2\) this leads to a maximum pressure of 1.3 MPa (critical point). The maximum operating temperature of 25 K leads to a minimum working pressure of 0.4 MPa. By increasing the minimum pressure from ambient pressure level, LH\(_2\) is prevented from boiling. The flow temperature of the LH\(_2\) is theoretically limited by its freezing temperature. A higher temperature increases the efficiency of the refrigeration cycle but has the disadvantage of a lower usable temperature span and thus a reduced length between the cooling stations. As a starting point, 20 K is used. The optimal temperature has to be determined with an analysis of the overall system, including the circulating pump, heat loads, capital and operational costs etc.

3. Selection of a cryogenic mixed refrigerant
At the required temperature range, only hydrogen and helium are possible pure refrigerants. Both offer excellent heat transfer properties, but have a low molecular weight, requiring a high number of stages for compression in a turbo compressor. Neon is a heavier gas, but has inferior heat transfer properties compared to hydrogen or helium. Mixing neon to helium can reduce the number of stages required for compression in a turbo compressor significantly and thereby reduce the investment cost [17]. To avoid solidification of the neon, a cycle using a mixture with neon is limited in its achievable cooling temperature. In order to use the advantages of a refrigerant containing neon, the latter has to be removed from the mixture before reaching temperatures below 25 K. The residual content should be low enough to prevent freezing completely or at least low enough to avoid damage of the turbo expander and plugging of the equipment by the neon snow. By cooling a mixture of neon and helium below its dew point, a part of the neon can be liquefied and subsequently removed. Following Dalton's law and assuming that the partial pressure equals the vapor pressure, it can be calculated that at a pressure of 10 bar and
Table 1. Thermophysical properties of neon, hydrogen, and helium at STP [16]

| Property                      | Neon    | Hydrogen | Helium  |
|-------------------------------|---------|----------|---------|
| thermal conductivity $\lambda$ [mW/(m K)] | 45.4    | 173.5    | 146.2   |
| isobaric heat capacity $c_p$ [kJ/(kg K)] | 1.03    | 14.20    | 5.19    |
| density $\rho$ [kg/m$^3$]    | 0.8998  | 0.0899   | 0.1785  |
| viscosity $\eta$ [$\mu$Pa s] | 29.38   | 8.38     | 18.69   |
| molecular weight [g/mol]     | 20.179  | 2.0159   | 4.0026  |

a temperature of 26 K, a neon fraction of 7.16% remains in the gas phase.
The addition of a second condensing, more volatile component, can reduce the remaining neon content in the gas. The only substance with a boiling curve between the ones of neon and helium is hydrogen. A mixture containing 22.5 mol – % hydrogen, 27.5 mol – % neon and 50 mol – % helium has a molar mass of 8.004 mol kg$^{-1}$. This is close to the molar mass of a mixture of helium with 25 % neon (8.047 mol kg$^{-1}$), which was proposed in a previous publication [17] and allows to safe half of the compressor stages.

4. Ideal system
For the following investigation all mixtures are considered ideal. From Raoult’s law, the binary pressure composition diagram for neon and hydrogen can be drawn. Figure 4 (left side) shows the theoretical boiling and dew curves for a temperature of 26 K. At this temperature and a pressure of 1.87 bar, the mixture is in the two phase region. The liquid phase contains 35.9 mol – % hydrogen, whereas the vapor phase contains 75.5 mol – % hydrogen. The initial composition is 45 mol – % hydrogen with respect to the condensible gases. Helium is considered a non-condensing gas and non-soluble in the liquid phase and therefore neglected in this step. The vapor and liquid fractions of neon and hydrogen can be derived from the known compositions and the conservation of the amount of substance. With respect to these two gases only, a liquid fraction of 76.96 mol – % follows. Taking helium into account, this value reduces to 38.48 mol – %. This liquid fraction can be drained in a phase separator. The remaining gas composition is 14.13 mol – % hydrogen, 4.59 mol – % neon and 85.87 mol – % helium. The remaining neon content in the gas can therefore be reduced significantly by the addition of hydrogen.
The pressure that can be read from the p-x diagram equals the partial pressure of neon and hydrogen in the ternary mixture. Applying Dalton’s law to the known composition of the gas, the total pressure can be calculated to 1 MPa.

5. Available fluid property data
The above considerations are under the assumption of ideal behavior of the mixture. For each of the three binary mixtures fluid properties are available, but to the knowledge of the authors, vapor liquid equilibria of the ternary mixture have not been investigated. For the gas phase For the system neon and hydrogen, data on phase equilibria is available [18] and given in figure 4 on the right side. The vapor pressures are generally higher compared to the ideal system and there is a positive azeotrope at high hydrogen concentrations. There is also a line in the phase diagram, where two liquid phases aswell as a gas phase form.
Figure 2. possible cycles, left: single separator, right: addition of a second separator to use the heat of evaporation of hydrogen

The above calculations can be applied to this phase equilibrium data. The point given in the diagram is at 0.365 MPa, which refers again to a total pressure of 1 MPa. The resulting neon content in the gas is 8.78 mol-% and therefore higher than without the addition of the hydrogen. It should be noted however, that this is under the consideration of the validity of the above assumptions and that the p-x diagram of neon and hydrogen can be extended to the ternary mixture.

6. Possible refrigeration cycles
On the basis of the above described fluid parameters a preliminary cycle layout can be defined as given on the left side of figure 5. The mixture is compressed in a multistage centrifugal compressor and recooled to ambient temperature. After that, it enters two counterflow heat exchangers in series with a pre-cooling turbine in between. A three stream heat exchanger follows in which the mixture is further cooled down to 26 K, liquefying most of the neon and part of the hydrogen. The liquid fraction is subsequently drained and expanded into the low pressure stream. The vapor fraction is superheated in the counterflow heat exchanger to avoid solidification of the hydrogen. By first cooling the complete mixture down to 26 K and reheating the gas phase to 30 K, the neon content in the gas phase can be reduced while avoiding temperatures below 19 K at the outlet of the turbine.

The vapor liquid liquid equilibrium offers an additional possibility to improve the efficiency of the process. Liquid hydrogen and liquid neon will separate at certain pressures, for example at 26 K at about 0.44 MPa (horizontal line in 4 right). Therefore the liquid fraction of the first phase separator, as shown in 5 on the right, can be expanded into a second phase separator,
where the lighter liquid hydrogen fraction can be decanted and expanded into the stream coming from the turbine. The heavier liquid neon is expanded directly into the low pressure stream after the load heat exchanger to avoid solidification.

7. Conclusion
An efficient refrigeration cycle utilising the three component mixture of neon, hydrogen, and helium seems to be a promising solution for recooling the cooling agent of a long distance sc cable. First calculations, assuming ideal mixtures, have shown that such a process can be established and that it would result in improved efficiencies compared to a standard helium refrigerator. Using the available, limited data for the mixture however showed a negative effect on the removal of neon. But the thermophysical properties of the three component mixture neon, hydrogen, and helium are rather unknown. Therefore, a detailed analysis of these properties has to be conducted with a respective cryostat. With the knowledge of the accurate phase behavior, the feasibility of the concept can be reevaluated and the proposed cycle can be readjusted including the specification of the components, especially the allowable solid fraction in the turbine stream.

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