Analysis and optimization of the liquid nitrogen pre-cooling stage for the EAST helium refrigerator

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Abstract. Pre-cooling of helium with liquid nitrogen is a good alternative to large scale helium refrigerators for initial cool-down from room temperature to about 80 K due to high exergy efficiency, high cooling capacity, and low demand of heat exchanger area. However, during the initial cool-down, two problems have to be faced for an improper liquid nitrogen pre-cooling stage arrangement. The temperature difference between helium and nitrogen at the cold end of the first heat exchanger became very large, which lead to high thermal stress and potential damage. The outlet temperature of the nitrogen stream of the heat exchanger is lower than room temperature, thus the efficiency decreases and more liquid nitrogen is consumed. In this paper, the performance of a liquid nitrogen pre-cooling stage for the EAST 2kW/4.5K helium refrigerator during cool-down phase will be analyzed. Then a new arrangement will be sought to avoid a larger temperature difference and underutilization of nitrogen cold energy. The current work may help to design, optimize and operate the liquid nitrogen pre-cooling stage for large scale helium refrigerators.

1. Introduction
Pre-cooling of helium with liquid nitrogen in a helium refrigerator is a good alternative as it presents several advantageous features such as fewer expanders, smaller compressor system, and small size cold box, which reduces the investment cost of the system for a given capacity [1]. Besides, it increases the rate of liquefaction and permits the initial cool-down from room temperature to about 80 K.

However, higher thermal stress and lower efficiency are two problems that have to be faced with for an improper liquid nitrogen pre-cooling stage arrangement during the initial cool-down. The temperature difference between helium and nitrogen at the cold end in the first heat exchanger became very large, which leaded to high thermal stress and potential damage. Stanford linear accelerator center (SLAC) was just one of the places where damage to the first main helium/helium/nitrogen heat exchanger had occurred [2]. The outlet temperature of the nitrogen stream of the heat exchanger is much lower than room temperature, thus the efficiency decreases and much more liquid nitrogen is consumed.

Some researchers have been carried out for the liquid nitrogen pre-cooling stage. U Wagner [3] reviewed several arrangements for the liquid nitrogen pre-cooling stages and their merits. P Knudsen and V Ganni [1] investigated the sensitivity of the key design parameters of the liquid nitrogen pre-cooling stage. T B Weber et al [2] proposed a different and unique process for the liquid nitrogen...
pre-cooling stage for the rapid cool down to 80 K. Z. G Zhu et al. [4] analyzed thermodynamic performances of the 310-80K precooling stage respectively with liquid nitrogen and turbines for the helium refrigeration and liquefaction cycle.

In this study, present status of the liquid nitrogen pre-cooling heat exchangers for the EAST 2kW/4.5K helium refrigerator is summarizing and analyzed. Then a new arrangement will be sought to avoid a larger temperature difference and underutilization of nitrogen cold energy. The current work may help to design, optimize and operate the liquid nitrogen pre-cooling stage for large scale helium refrigerators.

2. Liquid nitrogen pre-cooling stage of the EAST helium refrigerator.

As shown in Figure 1, the liquid nitrogen pre-cooling stage for the EAST helium refrigerator is composed of a plate-fin heat exchanger (PFHE) EX1 with serrated fins and a liquid nitrogen tank with a coil heat exchanger EX9. The PFHE core and serrated fins are depicted in the Figure 2.

For EX1 and EX2, energy balances give

\[ m_{HP}(h_i - h_2) = m_{LP}(h_2 - h_4) + m_{SP}(h_7 - h_9) + m_{N2}(h_{10} - h_9) \]  
(1)

\[ m_{LP}(h_2 - h_3) = m_{N2}(h_9 - h_8) \]  
(2)

Figure 1. Simplified process flow of the EAST helium refrigerator

Figure 2. Schematic diagrams of the PFHE core (left) and serrated fins (right)
where \( m \) is mass flow rate of stream, \( h \) is specific enthalpy of the fluid.

![Flowchart of the EAST liquid nitrogen pre-cooling stage](image)

Figure 3. Simple flowchart of the EAST liquid nitrogen pre-cooling stage

The design parameters of the heat exchanger EX1 is shown in Table 1. It has a total 68 passages, of which 22 are assigned to the hot high pressure (HP) helium while remaining 20, 20 4 and 2 are assigned to the cold low pressure (LP), sub-pressure (SP) helium gas, nitrogen gas (N2) and dummy layers respectively [5].

| Item                  | Unit | HP Helium | LP Helium | Sub-P Helium | Cold Nitrogen |
|-----------------------|------|-----------|-----------|--------------|--------------|
| Inlet temperature     | K    | 300       | 77.8      | 77.8         | 78.8         |
| Inlet pressure        | Bar  | 19.5      | 1.1       | 0.37         | 1.15         |
| Outlet temperature    | K    | 90.09     | 293       | 293          | 293          |
| Mass flow rate        | g/s  | 213.26    | 148.51    | 48.24        | 57.4         |
| Allowable pressure drop | kPa | 1         | 3.5       | 1.5          | 1            |
| Number of layers      | /    | 22        | 20        | 20           | 4            |
| Heat transfer area    | m²   | 138       | 325       | 207          | 65           |

![Graph of temperature difference](image)

Figure 4. Temperature difference between the nitrogen and helium streams of EX1 cold end
During the initial cool down in 2016, the temperature difference between the nitrogen and helium stream at the cold end of the heat exchanger EX1 was large, which is shown in Figure 4. To keep thermal stresses within the acceptable limits, it is suggested that the maximum permissible temperature difference between streams of brazed aluminium PFHE is approximately 50K [6].

The temperature differences between HP and LP helium, SP helium stream are depicted in the Figure 5. Both in the warm end and cold end, the temperature differences in the process of the initial cool-down were very large. It is difficult to handing this in this arrangement of the liquid nitrogen pre-cooling stage. After the completion of the cool-down, the temperature differences came to the reasonable and desired value.
When the initial cool down started, the HP stream outlet temperature of the EX1 began to decrease from room temperature, as shown in the Figure 6. In this moment, the HP stream mass flow rate was small due to higher temperature and lower helium density. However, it increased with the decrement of the HP outlet temperature $T_2$. High outlet temperature of the EX1 HP stream and continual growth of mass flow rate leaded to a large amount of liquid nitrogen evaporated in the liquid nitrogen tank. Therefore, the consumed liquid nitrogen in the cool-down period is much more than designed value, as seen from the Figure 7. Due to large heat capacity in the N2 stream and limited to heat exchanger area, the N2 stream outlet temperature of the EX1 was lower than room temperature. The lowest temperature is about 200K and this causes frost on the outer surface of the nitrogen gas exhaust pipe.
3. New arrangement of liquid nitrogen pre-cooling stage

To avoid a large temperature difference and liquid nitrogen demand in initial cool-down, a new arrangement of the liquid nitrogen pre-cooling stage for the EAST helium refrigerator is shown in the Figure 8. The nitrogen channel and some part of the high pressure helium channel are separated into a new heat exchanger EX1_N. With right control valves, this arrangement is adapted to the cool-down adjustment and the control of cooling rate. When initial cool-down start, most of the HP helium will be feed into the EX1_N channel. And the N2 outlet temperature can kept at room temperature range by adjust the opening of CV1 and CV2.

For EX1_H, EX1_N and EX2, mass and energy balances give

\[ m_{HP-H}(h_{11} - h_{12}) = m_{LP}(h_{15} - h_{14}) + m_{SP}(h_{17} - h_{16}) \]  (3)

\[ m_{HP-N}(h_{11} - h_{12}) = m_{N2}(h_{20} - h_{19}) \]  (4)

\[ m_{HP} = m_{HP-H} + m_{HP-N} \]  (5)

\[ m_{HP}(h_{12} - h_{13}) = m_{N2}(h_{19} - h_{18}) \]  (6)

After the completion of initial cool-down, the parameters of EX1_H and EX1_N is shown in the Table 2. The only difference between existing EX1 and EX1_H, EX1_N is that mass flow rate of HP stream is identical.

| Items                          | EX1_H   | EX1_N   |
|-------------------------------|---------|---------|
| **Channel**                   | HP-He   | LP-He   | Sub-P He | HP-He | N2       |
| **Inlet temperature (K)**     | 300     | 77.8    | 77.8     | 300   | 78.8     |
| **Inlet pressure (Bara)**     | 19.5    | 1.1     | 0.37     | 19.5  | 1.15     |
| **Outlet temperature (K)**    | 90.09   | 293     | 293      | 90.09 | 293      |
| **Mass flowrate (g/s)**       | 201.6   | 148.51  | 48.24    | 11.62 | 57.4     |
4. Summary
In this study, operation status of the liquid nitrogen pre-cooling stage of the EAST helium refrigerator during initial cool down period is given. From the cool down curve, the first heat exchanger EX1 has to suffer from a large temperature difference and potential damage both at warm and cold end. Due to a large amount of evaporated nitrogen and limited to heat exchanger area, the N2 stream outlet temperature of the EX1 is lower than designed value. A new arrangement of the liquid nitrogen precooling stage with two separated heat exchangers is sought to avoid those problems. At last, the theory formulas and operation parameters of these two separated heat exchangers of the new arrangement is presented.

References
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