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Study of operational modes of cool-down and warm-up processes for the ESS large-scale 20 K helium refrigeration system

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Abstract

In the beginning, the European Spallation Source (ESS) will install two hydrogen moderators above the tungsten target wheel where the nuclear heating is estimated to be 6.7 kW at the proton beam power of 5 MW. The ESS cryogenic moderator system (CMS) has a function to circulate a subcooled liquid hydrogen (17 K and 1.1 MPa) through the moderatos and is cooled through a heat exchanger by a large-scale 20 K helium refrigeration system with a cooling capacity of 30.3 kW at 15K, which is called Target Moderator Cryoplant (TMCP). Commissioning of a TMCP cold box and two compressor skids had been completed in 2019. 300 m-long cryogenic transfer lines (CTL) and a valve box located next to the CMS cold box have been installed in the summer of 2022. In this paper, we studied to establish the TMCP cooldown and warm-up processes and optimise the operational parameters based on the result of the CMS cooldown simulation.

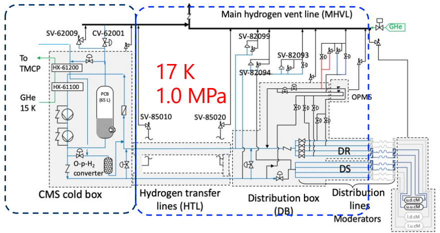
1. Introduction

At the ESS target, high energy spallation neutrons are produced by impinging 5 MW proton beam on tungsten.

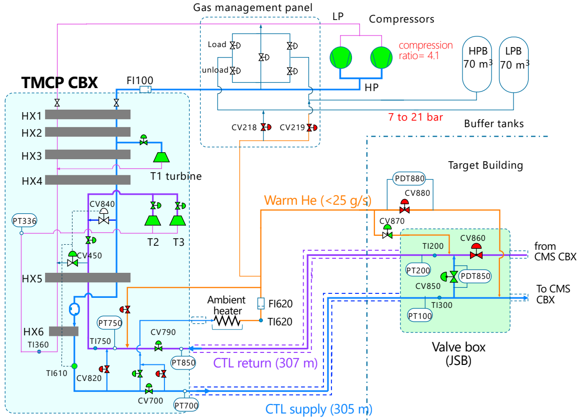
- Pulsed proton beam: Repetition of 14 Hz and a pulse length of 2.86 ms.
- Spallation neutrons are moderated to cold and thermal energies by the moderators.
- The nuclear heating at two hydrogen moderators is estimated to be 6.7 kW for the 5-MW proton beam power.

(For four (two above and two below the target wheel, respectively) in the future where the nuclear heating: 17.2 kW.)

➡ Cryogenice Moderator System (CMS) has been designed and is cooled by a large-scale 20 K helium refrigenration system (TMCP) (30.2 kW at 16 K) via a heat exchanger.



TMCP (Target Moderator CryoPlant) – completely installed in 2022



- A temperature controller regulates the CTL supply temperature (TI610) by acting two bypass valves (CV450 and CV840).
- HP helium with a temperature of 16 K (~1 kg/s) is delivered to a valve box (JSB) via the 300-m long CTL
- CMS supply temperature (TI6630) will be fine-tuned at 16.4 K by mixing the warm helium through CV880 in order to absorb the CTL supply temperature fluctuation of less than 0.4 K.
- CTL return temperature (TI200) will be controlled at 21.2 K by CV870.
- A fraction of the 16-K HP helium flow (< 25 g/s) feeds through an ambient heater.

In this study,

TMCP operational procedures of the cooldown and warm-up have been studied based on the simulation results (C1Or2B-03) and their parameters were optimized.

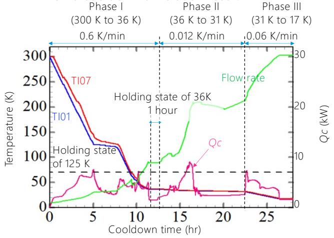
2. Study of TMCP cooldown operaiton

2.1 Required TMCP cooling capacity

Tatsumoto et al. [C1Or2B-03] has carried out the simulation of the CMS cooldown process, which is divided into three phases.

- PHASE I (300 K to 36 K): 0.6 K/min, Q_c< 7 kW
  - -Feed helium temperature is maintained at 125 K.
  - -CMS pressure: 11 bar
- PHASE II (36 to 31 K): 0.012 K/min Q_c< 9.2 kW
  - - CMS pressure: 13.5 bar
- PHASE III (31 to 17 K): 0.06 K/min, Q_c< 7 kW
  - - CMS pressure: 11 bar

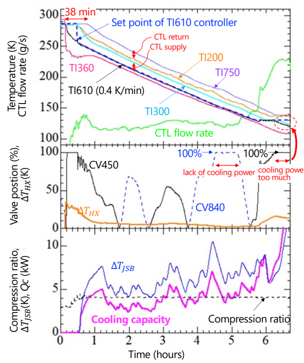
CMS cooldown simulation result



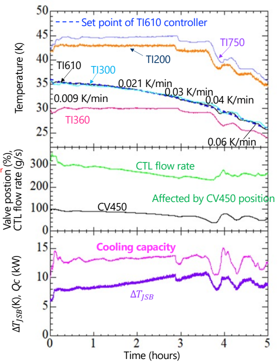
2.1 TMCP cooldown using one of the parallel cold turbine (T2 or T3)

- One compressor, the warm turbine (T1) and one of two cold turbines (T2) were operated.

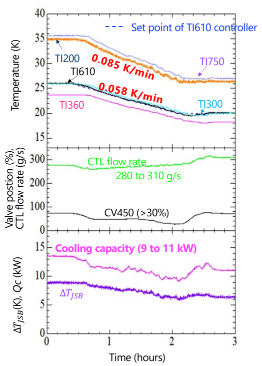
PHASE I cooldown (HP= 17 bar)



PHASE II cooldown (HP = 14.5 bar)



PHASE III cooldown (HP= 14.5 bar)



- At the beginning, HP was reduced to 10 bar and the compression ratio was also resuce to 3.0 (for the HX protection) (ΔT_{HX} =35 K< 40 K)
- Cooling speed = 0.4 K/min < 0.6 K/min.
- Available cooling capacity = around 4 kW <7 kW.

-> NOT meet the requirement.

- Cooling speeds were changed
- CTL return temperature was adjusted at CV450 >50%.
- Cooling capacity is around 12 kW > 9lW (max).

->meets the requirement.

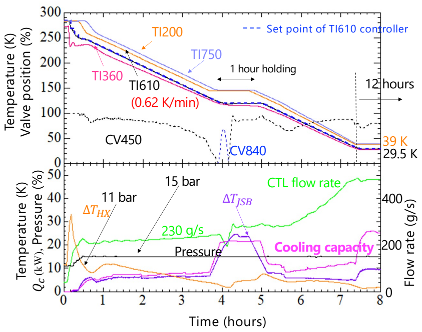
- Cooling capacity > 5.5 kW

-> meets the requirement.

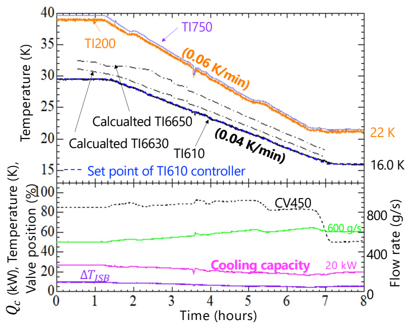
2.2 TMCP cooldown using both of the parallel cold turbines (T2 AND T3)

- Two compressors,the warm turbine (T1) and both of two cold turbines (T2) were operated.

PHASE I & II cooldown (HP= 15 bar)



PHASE III cooldown (HP = 15 bar)



- HP at the beginning=11 bar (compression ratio =3.6) ΔT_{HX} =34 K (< 40 K)
- Cooling speed = 0.62 K/min (> 0.6 K/min.)
- Temperature controller (TI610) is not suitable for a transient phenomenon.
- Available cooling capacity = around 8.1 kW below 150 K (> 7 kW.)

, more than 9 kW in Phase II and more than 17 kW in Phase III.

-> meet the requirement.

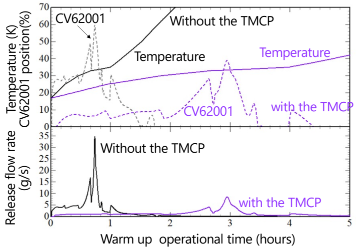
Optimized parameters

- HP =15 bar
- Cooling speed (TI610 and TI200) in each phase.
- Temperature controller (TI610) : maintain the CV450 position above 80%.
- CV880 in the JSB should be used to fine-tune the He feed temperature to the CMS.

3. Study of TMCP warm-up operaiton

3.1 CMS warm-up simulation

CMS warm-up simiulation for Phases I and II from 17 K to 40 K was carried out using the code by Tatsumoto et al. [C1Or2B-03].



Heat source: Static heat loads (4.7 kW)

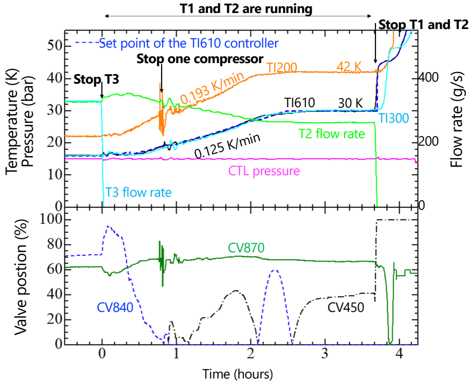
- Mainly coming from two hydrogen pumps
- P_{H2} = 13.5 bar > critical pressure of 12.9 bar

- For the warm-up without the TMCP, although the warm-up time gets shorter, the H2 release control valve (CV62001) rapidly changes and increases to 60% to maintain the pressure at constant.

In Phsae I & II (liquid phase), the watm-up speed should be controlled using theTMCP.

- Cooling power is enough.
- Two compressors and two cold turbines are not needed.
- 0.0125 K/min (Phase I) and 0.022 K/min (Phase III)

3.2 TMCP warm-up operation



PHASE I

- When one of the compressors was stopped, a rapid change in flow rate by 30 g/s made the PID control of TI200 oscillate. (TI200 cpntroller PID tuning issue for the transient process)
- TI610 controller seems to work (valve positions < 90%)
- Warm-up operation has been completed within 3 hours.

PHASE II

- CTL supply temperature (TI610) and the CTL return temperature (TI200) will be maintained at 30.0 K and 42.0 K as well as the Phase II cooldown process
- the CMS supply temperature will have to be fine-tuned at the desired warm-up speed of the CMS by CV880.

PHASE III

- It is not necessary to slow down the CMS warm-up by controlling the TMCP cooling capacity.
- We stopped the warm turbine (T1) and the other cold one (T2) in turn
- While both of the cold turbines stop, the temperature controller is deactivated. The turbine bypass valve (CV450) opened to 100% in order to make a circulation flow over the TMCP cold box.
- The supply temperature (TI610) rapidly increased to 44 K and the temperature rise at TI300 in the JSB appears after 5 minutes.

➡ CMS supply temperature has to be increased up to more than 44 K by CV880 before the transition from Phase II to III to avoid the rapid temperature change in the hydrogen loop

4. Conclusions

- TMCP cooldown and warm-up process have been studied based on the simulation results for the CMS cooldown and warm-up operation.
- It turned out that the two cold parallel turbines were needed to achieve the required CMS cooldown operation because most of the cooling capacity was consumed to cool the 300 m-long CTL.
- The TMCP cooldown operational procedure has been established and its operational parameters have been optimized.
- In the Phase I warm-up process, the supply temperature was successfully increased to 30 K, controlling the cooling capacity of the TMCP that operates the T1 and either of T2 or T3.