20 K Cryogenic Helium Forced Flow Circulation Loop

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ABSTRACT

MgB2 based superconducting electro-technical applications under development require distributed high cooling power in the 20 K temperature range. For such applications, Absolut System designed a supercritical (20 bar) helium forced flow circulation loop with a net cooling power in the range of 70-100 W at 20 K.

The circulation loop makes use of two Cryomech AL325 mono stage Gifford-MacMahon type cryocoolers as the cold source. In order to enhance the efficiency and to reduce the foot print, a Noordenwind type cryogenic circulator from Cryozone is used for the forced flow instead of a traditional room temperature compressor and counterflow heat exchangers. Thermal shielding is provided with lost LN_2 open loop forced flow.

The design optimizations will be reported in this paper, as well as outcomes of manufacturing and preliminary performance testing.

INTRODUCTION

Absolut System has developed and produced [1, 2] several remote helium cooling loop systems ranging from 30 W @ 50 K to 80 W @ 30 K using helium room temperature compressor packages as circulators to flow the required helium mass in a closed loop to the recuperator heat exchangers, the cold head heat exchanger, the transfer line and the application heat exchanger to absorb the heat load.

Potential application is to cool down and operate a MgB2 based superconducting cable system at 20 K. The objective helium mass flow should be in the range of 10 g/s.

Commercial compression units providing such a mass flow require a large foot print, a high electrical input power and are expensive. Such a mass flow does not cope with the use of cold check valves to convert a small portion of the oscillating flow from the GM compression unit to circulating flow for the loop as proposed by Cryomech [3].

The conductor 20 K cooling will be provided by a supercritical (20 bar) helium forced flow closed loop implemented by a mono stage GM type cryorefrigerators and a cold pump.

The Piping and Instrumentation Diagram (P&ID) of the 20 K cryorefrigeration closed loop is found in Figure 1.

DESCRIPTION OF THE SYSTEM

The cryogenic helium circulation loop gathers the following components identified on the P&ID:

- One Cryostat interfacing with two cryorefrigerators cold heads, I/Fs with the cryofan, Johnston coupling K13 female Input/Output cold helium ports, Input/Output LN2 ports, GHe Inlet port, ISO K100 vacuum port mated with a gate valve and three KF40 ports.

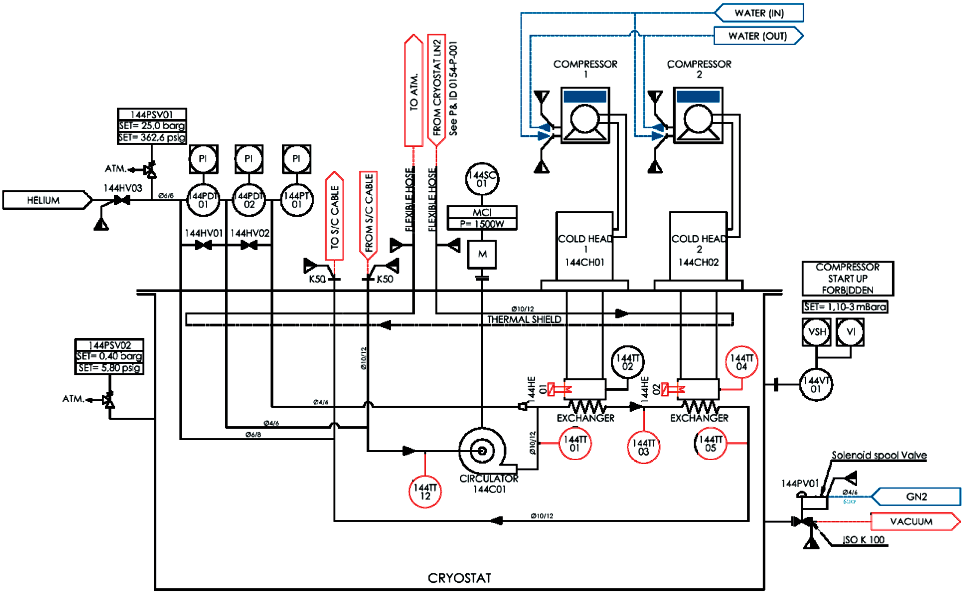

Figure 1. Piping and Instrumentation Diagram of the 20 K cryorefrigeration closed loop.

- Two Cryomech AL325 type cryo-refrigerator systems providing cooling power at 20 K and consisting of:
  - Two Cryomech AL325 cold heads (CH01 and CH02) mated to a cryostat upper flange,
  - Two Cryomech CP1110 helium Compressor Packages connected to the cold heads via two (LP and HP) helium flex lines 3 meters long and a cold head motor cord.
- One Cryofan cold pump (144C01) Noordenwind type from Cryozone for a supercritical helium forced flow at 20 bar.
- One pair of Cryoflex transfer lines type DN12/DN32 terminations K13 He male, 4.4 meters long, for Input/output to the S/C cable with cold helium flow at 20 bar.
- One pneumatic single-acting vacuum gate valve (144PV01) for 20 K cryostat vacuum insulation.
- One vacuum gauge (144VT01).
- One vacuum safety relief valve (144PSV02).
- Six calibrated Lakeshore Cernox type CX-1070-CU-HT-4L-QT temperature sensors (144TT01 to 144TT05 & 144TT12) to control the temperature at the cold heads and at the inlet and outlet of the heat exchangers and the cryofan circulator.
- Two heaters 144HE01 & 144HE02 (1 at each cold head exchanger).
- Two differential pressure transmitters (144PDT01 and 144PDT02).
- One absolute pressure transmitter (144PT01).
- One high pressure safety relief valve (144PSV01).
- One GHe Inlet manual valve (144HV03), straight ball type valve.
- Two manual valves (144HV01 & 144HV02) for the by-pass of the pressure differential transmitters, angle pattern ball valve type.

The two AL325 cold heads have been specifically adapted by Cryomech with an efficient integrated cold heat exchanger equipped with 1/2” VCR type fittings as shown on the Figure 2. The copper heat exchanger is directly silver brazed around the expansion chamber of the GM cryocooler to reduce the thermal gradient.

Figure 2. Artist view of the Cryomech AL325 cold head with integrated cold heat exchanger.

The Noordenwind type cryofan from Cryozone used as the circulator in the forced flow loop is illustrated in the Figure 3. The cryofan consists of a high speed motor under helium pressure terminated with an elongated stainless steel shaft and a 31 mm impeller. It can operate between 6,000 and 21,000 rpm and sustain a maximum static system pressure of 30 bar. Pump housing has also been equipped with 1/2" VCR type fittings. A picture of the cryorefrigerator assembly is seen in Figure 4.

A copper thermal screen is used for the thermal shielding of the 20 K cold parts as shown on the Figure 5. This copper thermal shield is also composed of two flanges and a cylindrical shell. The upper flange of the copper shield is mechanically anchored to the upper flange of the cryostat thanks to low conductive struts made of G10 glass fiber. The upper flange of the thermal shield comprises a LN2 loop with In/Out fittings mated on the cryostat upper flange. The three parts of the copper thermal shield are separately wrapped into 20 layers of MLI.

Figure 3. Picture of the Cryozone Noordenwind type cryofan used as the circulator.

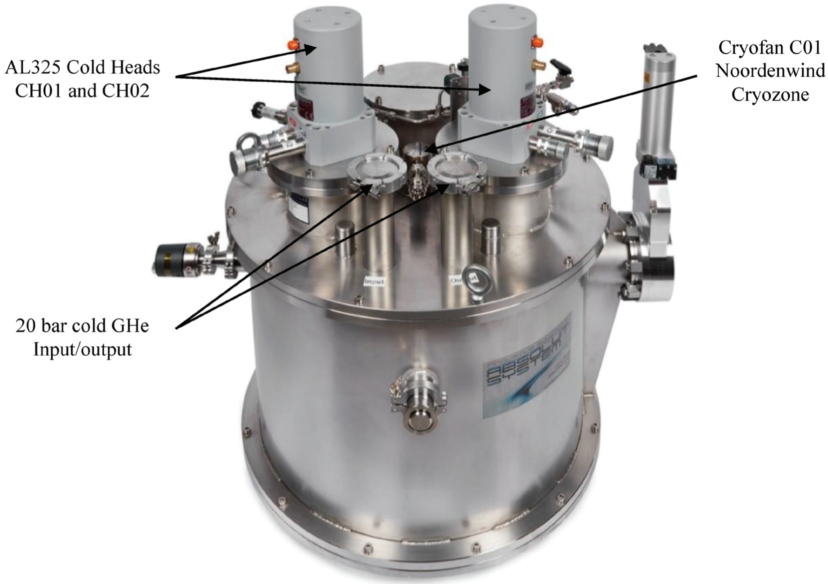

Figure 4. Picture of the 20 K cryorefrigeration closed loop overall assembly.

PERFORMANCE TESTS

Performances at cryocooler integration

The cryogenic performances of both AL325 cold heads have been measured with the cold heads integrated in the cryostat with the final Multi-Layer Thermal Insulation (MLI) and connected to the stainless steel piping. The circuitry is kept under vacuum to avoid any thermal loss via helium gas. The LN2 shield was cooled during the performance characterization tests. Thermal sensors 144TT02 & 144TT04 and heaters 144HE01 & 144HE02 have been used.

The performance is reported in Figure 6. Measured performance at Absolut System is slightly better that the one reported by Cryomech due to the use of a LN2 cold thermal screen at the 20 K cryostat.

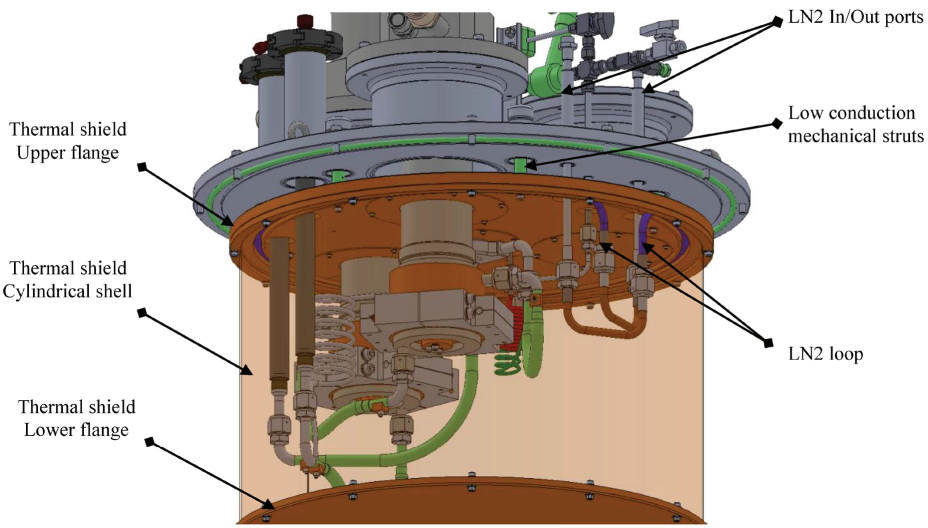

Figure 5. CAD view of the copper thermal shield.

20 K cryostat performance tests using a test cryostat

To simulate a future superconducting cable, a test cryostat has been manufactured and connected to the helium loop for the test campaign. Two different heat exchanger designs have been implemented to determine the effect on the 20 K refrigeration loop performances and estimate future performance expected with a superconductor cable. The test cryostat has been equipped with two temperature sensors and a differential pressure transducer to estimate the heat exchanger pressure drop and to discriminate the flexible helium lines pressure drops.

With this test configuration we are able to get sufficient information to measure and analyze the thermal losses and pressure drops of the main components of the helium cooling loop:

- Cold circulator,
- Cold heads heat exchangers,
- Helium flex lines,
- Test cryostat,
- Cable simulating heat exchanger.

A specific test has been performed with the helium loop by-passed through a single helium flex line to determine the helium flexible line pressure drop and thermal losses. A total of about 65 runs with different parameters set up have been performed and analyzed, covering a large range of parameters:

- Helium loop pressure: 10, 15, 17.5 and 20 bar (nominal).
- Cold pump rotation speed: 12.000, 12.500, 15.000, 18.000 and 21.000 rpm.
- Future superconductor cable heat losses: 25, 50, 75, 87.5, 100 and 125 W.
- Applied heat load on cryorefrigerators cold heads in the by-passed helium loop configuration: 75 W and 100 W per cold head.

Performance tests analysis

The helium mass flow rate is determined via a thermal balance at the cold head heat exchangers:

$$(Q_{\mathrm{CH01}} - Q_{\mathrm{CH02}}) = \dot{m}_{He}(h_1 - h_5) \tag{1}$$

Where,

Q_{CHO1} or Q_{CHO2} are respectively the thermal loads on cold heads 1 & 2 (watt).

$\dot{m}_{He}$ is the helium mass flow rate (g/s).

h_1 or h_5 are respectively the helium enthalpy at cold head 1 heat exchanger inlet and at cold head 2 heat exchanger exit (J/g).

Q_{CHO1} and Q_{CHO2} are determined from the cold head load curve measurements as reported in the Figure 4, using measured cold head temperatures (TT02 and TT04). From the above-calculated

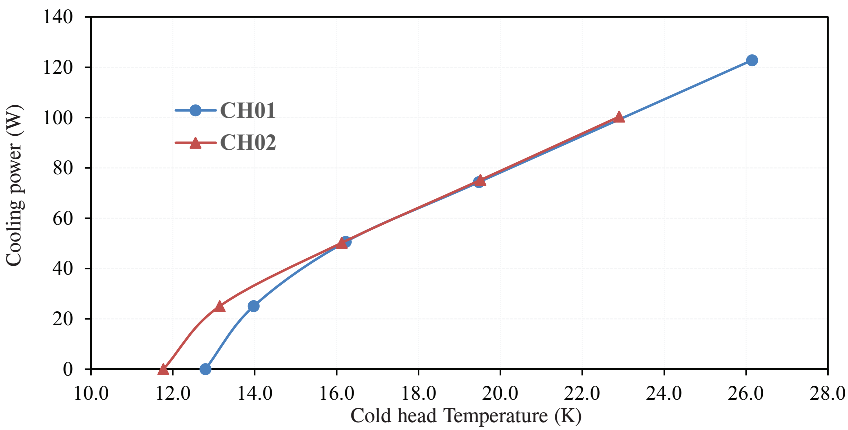

Figure 6. Performance characterization of two AL325 cold heads. Helium circuit pumped and LN2 thermal shield active.

helium mass flow rate $\dot{m}_{He}$ (Eq. 1), the the helium volumetric flow rate V_{He} (m^3/h) is determined, using the helium density ρ_{12} (kg/m^3) at cold pump inlet:

$$V_{He} = \dot{m}_{He}/\rho_{12} \tag{2}$$

From the measured differential pressure ΔP_2 (Pa) between cold pump inlet and outlet, the pressure head ΔH (m) delivered by the cold pump is calculated using the helium density ρ_{12} (kg/m^3) at cryogenic circulator inlet:

$$\Delta H = \Delta P_2/(\rho_{12} * g) \tag{3}$$

It is now possible to represent the cold pump hydraulic characteristics in a universal graph ΔH versus V_{He}.

In Figure 7, a graph to report the values obtained from all experimental tests performed is found: the points have been determined at different helium pressure, cold pump rotational speeds and thermal loads.

Three different sets of points can be observed corresponding to the three different test families: 20 K refrigeration system with by-passed test cryostat by connecting In/out of the loop with a single helium flex line (1 flexline only, by-pass) and two sets with helium circulation loop connected with a pair on In/Out flexlines to the test cryostat equipped with heat exchanger 1 (In/out flexlines + Exchanger 1) or equipped with heat exchanger 2 (In/Out flexlines + Exchanger 2).

Both heat exchangers are simulating the future superconductor cable. These three sets of points have been correlated with quadratic laws, the usual way to take into account linear pressure drops (in piping) and singular pressure drops (for cold head's heat exchangers and for different flow singularities such as elbows, restrictions or expansions in piping). We have also implemented "guides for eyes" on this graph corresponding to the different rotational speeds of the cold pump. The data is in quite good agreement with the curve based on measurements with air at 20°C and atmospheric pressure provided by Cryozone for the cold pump.

We also evaluated the hydraulic efficiency of the cold pump η_P. To do so we first calculated the "gross" heat dissipated by the cold pump:

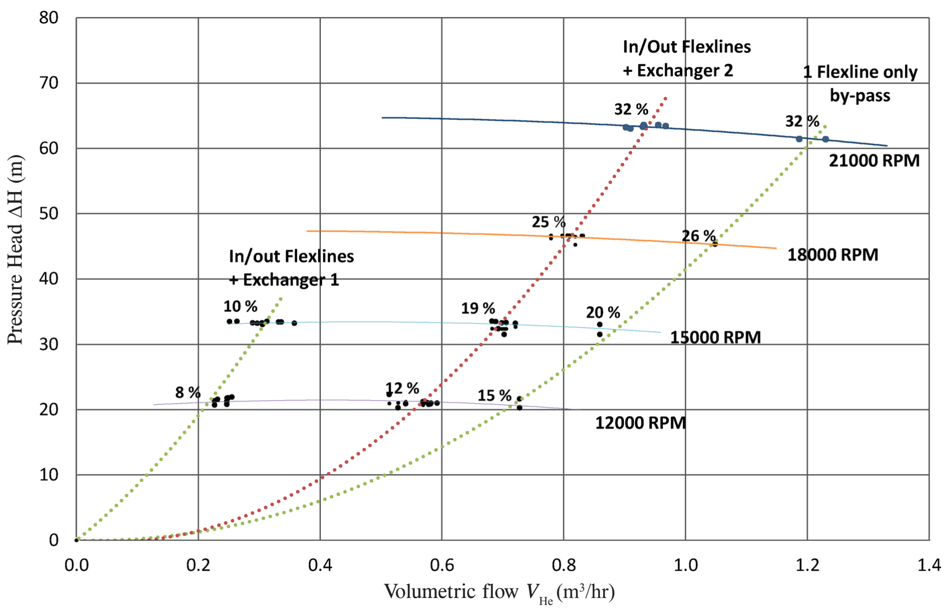

Figure 7. Measured hydraulic characteristics of cold pump and helium loop for various configurations and rotational speeds.

$$Q_{cold\,pump} = \dot{m}_{He} \,.\, (h_{12} - h_1) \tag{4}$$

This “gross” heat dissipation includes both static losses by thermal conduction through the cold pump shaft from room temperature and the actual dynamic work of compression. We used the static losses value (6 Watt @ 20 K) given by Cryozone in the technical documentation delivered with the cold pump and subtracted it from the “gross” heat to get the actual dynamic work of compression.

$$W_{comp} = Q_{cold\,pump} - 6 \tag{5}$$

The theoretical work of compression can be determined knowing the pressure drops on the pump sides (ΔP_2) and the calculated volume flow (Eq. 2).

$$W_{comp\,theo} = V_{He} * \Delta P_2 \tag{6}$$

Comparing the calculated actual work (Eq. 5) to the theoretical work of compression (Eq. 6), we can evaluate the cold pump hydraulic efficiency:

$$\eta_P = \frac{W_{comp\,theo}}{W_{comp}} = \frac{V_{He} * \Delta P_2}{Q_{cold\,pump} - 6} \tag{7}$$

The results are also reported in Figure 7. They are logical in terms of relative variation. In terms of absolute values these calculated efficiencies are smaller than those generally reported by Cryozone on their commercial brochures. In practice there is no efficiency data given nor guaranteed by Cryozone in the data package delivered with cold pump. Only the performance curves (pressure head versus volumetric flow for different rotational speeds) of the delivered cold pump are given. They are measured with air at atmospheric temperature and pressure. An explanation could also be the underestimated static losses.

Pressure drops analysis

From the differential pressure drop transducers (ΔP_1: 20 K cryostat inlet/outlet, ΔP_2: cold pump inlet/outlet, ΔP_3: test cryostat heat exchanger inlet/outlet) installed on the helium loop, we can determine the pressure drops at different subsystems level:

- Pressure drop in cold head heat exchangers: $\Delta P_2 - \Delta P_1$
- Pressure drop in helium flexible lines: $\Delta P_3 - \Delta P_1$

The contribution of the main helium loop components (cold head heat exchangers, helium flex lines, test cryostat heat exchanger) for different cold pump rotational speed is reported in Fig. 8 in terms of pressure drop (mbar). The values reported correspond to the tests performed with the second version of the test cryostat heat exchanger, which is the closest in terms of pressure drops of a superconductor cable.

It appears that the helium flex lines pressure drop contribution is quite significant (in the range of 100 to 150 mbar at 15,.000 to 18,000 rpm cold pump rotational speed and 10 g/s or 0.8/0.95 m^3/hr helium flow rate). A significant improvement can be done on these components.

The pressure drop in the heat exchanger simulating a superconductor cable (about 45 to 60 mbar at 15.000 to 18.000 rpm cold pump rotational speed and at 10 g/s or 0.8/0.95 m^3/hr helium flow rate) is significantly larger than that expected in a superconductor cable. This still allows for some margin in cold pump operation and cooling performances for future operation.

The pressure drop in the cold head heat exchanger is in agreement with our expectations for an efficient heat transfer as requested to minimize temperature gradients between cold head and helium in the cooling loop.

Thermal performances analysis

The foreseen operation pressure of the helium-cooling loop is 20 bar. We made some tests with lower pressure (17.5 bar, 15 bar and 10 bar). Performances are effectively better at 20 bar as

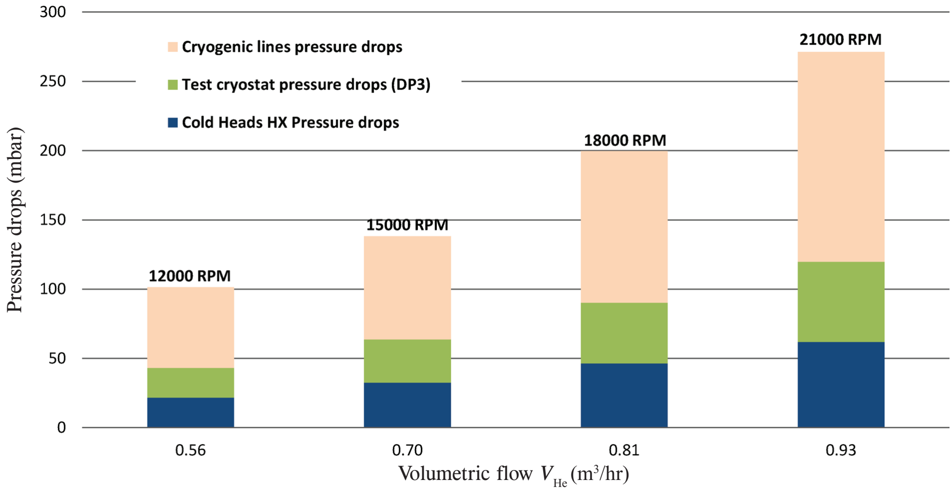

Figure 8. Relative contributions of cold head heat exchangers, helium flex lines and test cryostat heat exchanger to helium loop total pressure drop for different cold pump speeds (for test heat exchanger #2).

expected. We did not performed tests at higher pressure which would be even better since a typical superconductor cable burst disc generally set in the range of 25 bar.

To test and qualify the helium cooling loop thermal performances with the 20 bar nominal helium loop pressure, we applied progressively different thermal loads (25 W, 50 W, 75 W, 87.5 W and 100 W) on the heat exchanger simulating a superconducting cable via a resistive heater.

We report in Table 1 temperature measurements at different points of the helium cooling loop for test configurations representative of a superconductor cable operation: helium pressure 20 bar, cold pump rotational speed 15,000 rpm / 18,000 rpm and applied heat load of 87.5 W / 100 W.

With these operation parameters, the temperature at cable inlet (18.4 K to 19.2 K) and outlet (20.5 K to 21.4 K) are in good agreement with the requirement to have a cooling loop helium average temperature of 20 K.

An even lower temperature can be expected in a future cable operation due to the fact that a larger mass flow rate may be achievable with a lower pressure drop in the cable than in the test heat exchanger.

Table 1. Temperatures at different helium loop locations for representative heat loads and cold pump rotational speed (measurements performed at 20 bar).

Applied load (W) **Cold Pump speed (rpm)**	**100** **15.000**	**100** **18.000**	**87.5** **15.000**	**87.5** **18.000**
Cooling power at cable estimation applied load + test cryostat losses	~ 114 W	~ 113 W	~ 102 W	~ 100.5 W
TT_{12} Cold Pump inlet / (~ Cable outlet)	21.41 K	21.29 K	20.64 K	20.54.K
TT_{01} Cold Head #1 HX inlet	21.76 K	21.66 K	21.07 K	20.99 K
TT_{02} Cold Head #1	20.04 K	20.18 K	19.45 K	19.50K
TT_{03} Cold Head #2 HX inlet	20.15 K	20.29 K	19.48 K	19.64 K
TT_{04} Cold Head #2	18.90 K	18.95 K	18.38 K	18.50 K
TT_{05} Cold Head #2 HX outlet / (~ Cable inlet)	18.85 K	19.14 K	18.37 K	18.59 K

Table 2. Thermal loads or losses of different helium loop components for representative heat loads and cold pump rotational speeds (measurements performed at 20 bar).

Applied load (W) **Cold Pump speed (rpm)**	**100** **15.000**	**100** **18.000**	**87.5** **15.000**	**87.5** **18.000**
Cooling power at cable estimation applied load + test cryostat losses (W)	~ 114	~ 113	~ 102	~ 100.5
Mass flow rate (g/s) calculated	8.55	9.98	8.66	9.84
Volume flow rate (m^3/h) calculated	0.699	0.806	0.693	0.779
Cold pump heat dissipation (W) [Eq. 4]	17.4	21.4	21.8	25.9
2 x flex lines heat dissipation (W) [Eq. 8]	17.0	15.8	17.0	15.8
Test cryostat losses (W) [Eq. 10]	14.2	13.4	14.6	13.1

We can determine from the above temperature measurements and associated helium enthalpy the heat dissipation at some specific subsystems:

- Heat dissipated by cold pump: from previous Eq. (4)
- Thermal losses of a pair of helium flex lines, determined in a specific test with a single flex line connected to the cooling loop (by-pass test cryostat conditions):

$$Q_{flex\ lines} = 2 \cdot \dot{m}_{He} \cdot (h_{12} - h_5) \tag{8}$$

- Heat dissipated out of the 20 K cooling system cryostat, including 2 flex lines + test cryostat losses + test heat exchanger applied heat load:

$$Q_{out} = \dot{m}_{He} \cdot (h_{12} - h_5) \tag{9}$$

- Test cryostat losses:

$$Test\ Cryostat\ losses = Q_{out} - Q_{flex\ lines} - applied\ heat\ load \tag{10}$$

These thermal loads or losses are reported in the Table 2.

Measured cold pump heat dissipations are significantly larger than that evaluated. This can be explained by the measured lower efficiency of the pump than expected from Cryozone commercial documentation and also the larger overall loop pressure drop mainly in helium flex lines and test cryostat heat exchanger. The pressure drop in a superconductor cable will be lower than the one in test cryostat heat exchanger, resulting in less dissipation by cold pump.

Thermal losses measured for the pair of flex lines (about 16 to 17 W) are larger than those estimated. This can be explained by the fact that insulation performances are probably a bit worth than estimated.

The calculated test cryostat thermal losses are in the range of 13.1 W to 14.6 W. This corresponds to a future cooling power margin for a cable cooling (it is a reasonable value for a test cryostat without LN2 cooled thermal shielding).

CONCLUSIONS

A cryogenic helium forced flow circulation loop has been designed, manufactured and tested by Absolut System. It makes use of two Cryomech AL325 GM coolers connected in series with a Noordenwind type cryofan from Cryozone and a pair of 4.2 meters of cryoflex lines. A remote cooling performance of 113 W at 20 K has been demonstrated with 20 bar helium loop pressure and 18.000 rpm cryofan rotational speed.

Performances improvements are expected by reducing the pressure drop budget on the pair of flex lines and while connected to a superconducting cable demonstrator.

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