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Design details of the current lead test facility Karlsruhe (CuLTKa)

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Abstract. The new current lead test facility CuLTKa was successfully commissioned in 2014 at the Karlsruhe Institute of Technology, Germany. Towards the end of the year the first pair of High Temperature Superconductor current leads (CL) for the Japanese tokamak JT-60SA was tested. These CL have to carry currents of up to 26 kA and are cooled with helium (He) at two different temperature levels, 4.5 K and 50 K, respectively. After commissioning and test of the first pair another 24 CL will be tested until 2017. The facility consists of five cryostats: The first cryostat distributes the He coming from the 2 kW refrigerator to the different experiments in the ITEP. In the second one, with an integrated He-bath, the forced flow He for the CL is cooled down to 4.4 K and the 50 K He is piped through. In a valve box the He at two temperature levels is distributed to two test cryostats housing each one pair of CL. This paper describes the design of the facility from a cryogenic point of view starting from the basic demands. The overall setup is derived and particular details are explained. Some design calculations will be opposed to measured data from its real performance. In addition one major safety aspect is described.

1. Introduction

Successful High Temperature Superconductor (HTS) Current Lead (CL) developments in the Institute for Technical Physics (ITEP) in KIT started in the 1990s with the development of a 70 kA HTS-CL as a demonstrator for ITER [1]. In 2006 KIT got the contract to design, fabricate and test 16 HTS-CL for the stellarator Wendelstein 7-X. In 2010 an agreement of collaboration was signed with Fusion4Energy to construct and test 26 HTS-CL for the Japanese satellite tokamak JT-60SA. To enable a reliable, reproducible, flexible and swift testing of these CL it was agreed to design and build a dedicated test facility. In 2014 the Current Lead Test Facility Karlsruhe (CuLTKa) was commissioned together with the first pair of 26 kA HTS-CL.

To operate these HTS-CL helium at two different temperature levels at 4.5 K and 50 K at overcritical pressures are required. Further an electrical current capacity of up to 30 kA is needed. To measure heat loads in the order of 2 W a setup up with very low background losses is required. For more detailed information on the HTS-CL see [2].

The paper consists of two parts. First, considering cryogenics only, the design path towards the final facility is illustrated. Afterwards particular design aspects are highlighted. Subsequently some of these are compared to measured data to evaluate the accuracy of the design tools.

2. From basic design points to a first setup of CuLTKa

A general description of CuLTKa is described elsewhere [3; Paper under preparation]. Here a rather brief description will be given. For the following explanations the reader may refer to Figure 1.

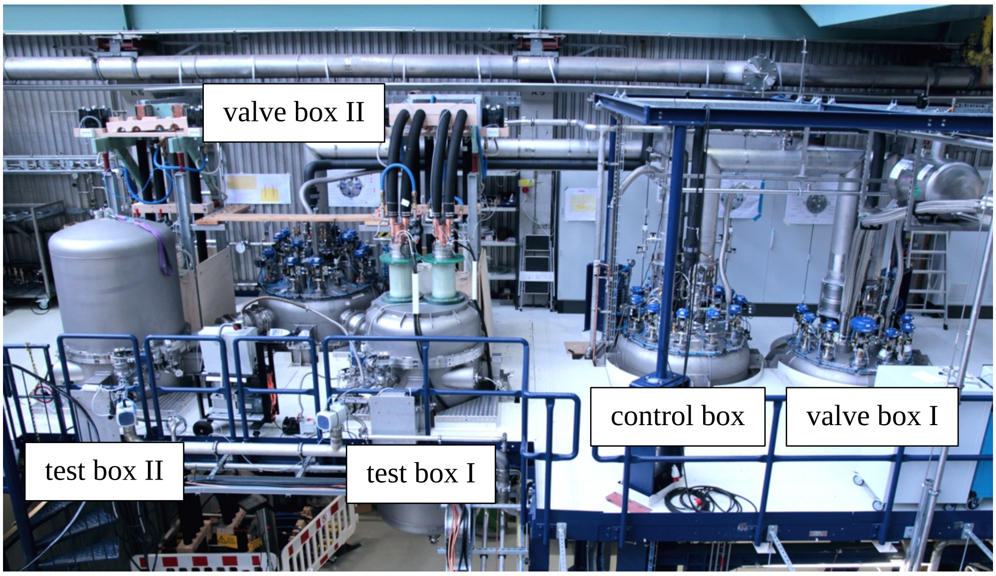

Figure 1. Photo of the Current Lead Test Facility Karlsruhe.

The facility consists of five cryostats connected by transfer lines which are mounted on an elevated platform to enable good accessibility to the inner cryostats by lowering the bottom parts. This also offers the opportunity of an inverted installation of the test boxes for future use.

The supply of helium at 4.5 K and 50 K at overcritical pressures can be provided by the refrigerator of the ITEP. Therefore the facility has to be integrated into an existing set of test facilities. Connected by transfer lines a valve box I is placed which distributes helium to different experiments. Due to transfer distances of up to 60 m and operating characteristics of the refrigerator an option for temperature adjustment at the experimental site is needed. This is realized with a cryostat working as a control box. In particular the temperature of the 4.5 K-helium flow is adjusted by using a 400 l-liquid helium (LHe) bath with an integrated coiled tube heat exchanger (HEX) that provides helium at overcritical pressures at 4.4 K.

The test setup comprises two CL short-circuited with a superconducting NbTi busbar operated at ca. 5 K. The test objects are installed in a test cryostat with an independent vacuum volume. The radiation shield of this cryostat is connected to the 50 K helium flow coming from the 2 kW refrigerator, which enables a controlled cool-down and warm-up of the radiation shield. To minimize the installation effort and the risk of sensor damages as well as He leakages this cryostat houses only piping and no electrical measurement equipment (except: temperature sensor on radiation shield). To optimize operation times of the refrigerator and test times a second test box was realized. Thus one cool-down and warm-up cycle permits the test of four CL. To distribute the helium to the two test boxes a valve box II was designed. It houses temperature, pressure and flow sensors required for the operation and the verification of the CL.

Both valve boxes and the control box are equipped with LN_2-shields. The vacuum system consists of two parts: an installation vacuum which is always maintained and the frequently pumped and vented test vacuum. The installation vacuum comprises valve boxes I and II, the control box and the transfer lines.

3. Design details

In all calculations the fluid and material properties were obtained from data bases like HePak [4] or Refprop [5] and Cryocomp [6] which can be integrated into common programs.

3.1. Pipe dimensioning and pressure losses

Starting from the draft of the previous section a plant model was realized. It provided a flexible tool to determine pressure losses and flow velocities. Resultant from these the mass flows and the corresponding pipe diameters could be derived. Input parameters are temperatures, pressures and mass flow rates of the two helium flows at entering the facility, as well as assumed heat loads along the transfer lines (based on experiments). It further can be differentiated whether two or four CL are installed. An underlying pressure loss calculation in pipes helps to determine the pipe diameters throughout the facility. It discriminates the flow conditions characterized by the Reynolds number according to the validity of common empirical approaches and for adjustable inner pipe roughness.

3.2. Stabilization of 4.5 K-level flow by a heat exchanger through a cooling LHe-bath

The narrow temperature range in which conventional superconductors as used in the short-circuiting busbar work demands well defined and stable temperatures. Temperature variations of the mass flow coming from the refrigerator due to thermal losses along the transfer line and to fluctuations of the control of the refrigerator have to be buffered. This is realized by integrating a LHe-bath in the 4.5 K-level. An immersed HEX pipe cools the inlet flow to 4.4 K while maintaining the pressure of the flow. This LHe-bath acts as a cooler for the 4.5 K He flow coming from the refrigerator. Figure 2 shows the setup as designed in CuLTKa.

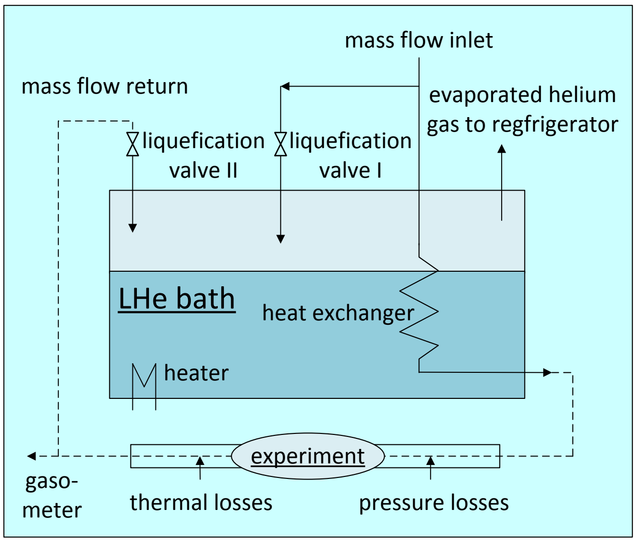

Figure 2. Flow scheme of the LHe-bath with its cooled HEX.

Figure 3 illustrates the thermodynamic benefit of the cooling effect of the LHe-bath. The pressure of the bath is determined by the intake pressure of the compressor station of the refrigerator which ranges around 1.15 bar. Assuming a helium inlet flow at 4.5 bar and 6 K (point 1a) a direct liquefaction with isenthalpic expansion yields roughly 60% helium gas (point 1b). In contrast a liquefaction of the precooled return flow at the same pressure and 4.4 K (point 2a) yields only a mass fraction of 5% gas (point 2b). To cool the flow from 6 to 4.4 K a specific heat of 11 kJ/kg has to be extracted (point 1a to 2a). This means by neglecting pressure losses a helium flow of 1 g/s could absorb 11 W on its way from the LHe-bath to and through the experiment and back to the liquefaction and would still provide 0.4 g/s of LHe, approximately.

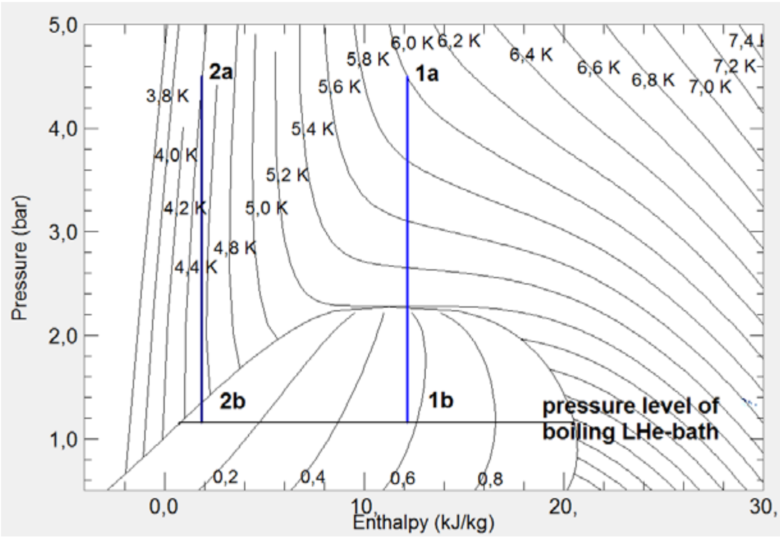

Figure 3. Comparison of two options for liquefaction into LHe-bath.

The size of the LHe vessel is assessed by the mass flow rate that is required for the cooling of the CL at the 4.5 K-level. A bypass between inlet and outlet flow in valve box II increases the flexibility and reliability, since a larger circulated mass flow experiences a smaller heat load per mass unit. On the other side the increase in pressure loss has to be considered already during design. This total mass flow needs to be cooled down close to LHe-bath temperature while passing through the heat exchanger. By taking this obtained heat input plus the estimated heat losses into the bath vessel an evaporation rate can be calculated. Neglecting any liquefaction into the vessel a holding time depending on the liquid volume of the vessel can be approximated. Assuming reasonable heat and pressure losses of the helium flow along its way to the experiment and back to the cooler a liquefaction rate as described above can be opposed to the evaporation rate. This estimation also shows boundaries to which level pressure and heat losses can be accepted.

The calculation of the heat transfer from the HEX to the LHe-bath is done according common approaches from literature. Given input parameters are the outer and inner pipe diameter, helium mass flow rate, helium inlet and outlet temperature, inlet pressure and the temperature of the LHe-bath. The calculation is done for 20 sections onto which the total amount of heat to be transferred is evenly divided. For each section the required length is determined. The calculation considers the heat transfer from the helium flow into the pipe depending on the flow conditions and the pressure loss and the heat transfer from the pipe into the helium bath. The heat transfer through the pipe wall is introduced as a mean value due to small variations of the material temperature along the pipe. Essential is also the calculation of the pressure drop along the pipe. In the final design calculation the input values have been set to the least favorable inlet flow conditions coming from the refrigerator and for an accepted temperature difference between bath and outlet of the HEX ($\Delta T_{bath\text{-}HEXout}$) of 0.2 K. Doing this the length pipe was determined to 50 m including 25% safety.

From point of safety consideration it has to be defined at which pressure the safety devices of this vessel open. With increasing blow-off pressure the mass flow rate and hence the size of the safety device decreases [7]. The mechanical stability of the vessel has to be determined during design phase according the maximum operating pressure. The design and construction of such a pressure vessel has to follow the pressure equipment directive (PED). For CuLTKa a combination of safety valve and burst disk was chosen where the valve with a rather small opening cross-section opens at 6 bar g and the burst disk designed for the maximum fault scenario opens at 10 bar g.

3.3. Valve design

In a separate design calculation the valve sizes were determined. Therefore valve flow coefficients K_{vs} for compressible and incompressible flows of the control valves are calculated. Input parameters are pressure, pressure loss over the fully opened valve, mass flow and temperature. Standard equations are used with no further coefficients applied. The calculation is done for four cases from which an appropriate K_{vs} has to be chosen. Four cases of operation:

- Case 1: ideal operation condition,
- Case 2: operation condition at minimum pressure, maximum mass flow and temperature,
- Case 3: operation condition at maximum pressure, minimum mass flow and temperature,
- Case 4: required mass flow at ambient temperature and maximum pressure.

For the chosen coefficient the valve characteristics as mass flow versus stroke are calculated and plotted for the input values of the four mentioned cases. Two diagrams for compressible and incompressible flow show each curve in linear as well as equal-percentage valve characteristic. The program further provides the opportunity of calculating different pressure losses over the valve for the chosen K_{vs}. This offers the user the opportunity to explore theoretical load limits for the particular valve.

4. Comparisons with measured data

4.1. Performance of the cooling LHe-bath

Table 1 shows the values of the design calculation, measurements and recalculated data from the measurements. For the recalculated measurement data the length was set to 50 m including a 25% safety margin and $\Delta T_{bath\text{-}HEXout}$ was obtained.

Table 1. Design data, measured and recalculated data of LHe-bath and HEX.

	Design	Measurement			Recalculation		
Bath pressure [bar]	1,15	1,16	1,14	1,16	1,16	1,14	1,16
Bath temperature [K]	4,36	4,37	4,35	4,37	4,37	4,35	4,37
Mass flow HEX [g/s]	10	8	9	9	8	9	9
Temperature HEX-in [K]	6	5,4	5,15	5,16	5,4	5,15	5,16
Pressure HEX-in [bar]	4	4	4,5	3,95	4	4,5	3,95
Temperature HEX-out [K]	4,57	4,4	4,37	4,38	4,43	4,4	4,43
$\Delta T_{bath\text{ - }HEX\text{-}out}$ [K]	0,21	0,03	0,02	0,01	0,06	0,05	0,06
Pressure drop HEX [mbar]	46	150	150	170	25	32	32

The initial purpose of this tool was a rough calculation in the design stage of the facility. What can be seen from these data is that the measurements show pressure losses which are three times as high as for the design calculation. Here it has to be mentioned that the presented pressure drop of the measurement includes a venturi pipe as well as a shut-off valve. Assuming a remaining pressure loss through a venturi of 25% of the differential pressure the pressure would drop about 42 mbar through the venturi. If the same amount is added for the shut-off valve the actual pressure drop through the HEX ranges slightly above the calculation. The comparison of measurement and design further shows a much smaller $\Delta T_{bath\text{-}HEXout}$ than expected.

During the measurements the mass flow to and from the experiment was fed and liquefied into the LHe-bath through liquefaction valve II, as illustrated in Figure 2. To run this process in stable conditions the heater was set to a heat input of 100 W. To illustrate this amount of power: an additional mass flow of 20 to 30 g/s with HEX-in conditions could be cooled to HEX-out condition. However for a practical realization the design of the HEX would need to be redesigned to such a large mass flow. Based on the measurements but assuming no liquefaction of the return flow the calculated theoretical holding time of a filled LHe-bath would be about 3 to 4 h. To balance in this case the evaporation by the HEX by an ideal liquefaction through liquefaction valve I a mass flow between 2 and 3 g/s is necessary.

Concluding from these considerations the LHe-bath with its integrated cooling HEX performs very well. A reliable and flexible system was realized. There is a relatively small deviation between design calculation for the HEX and the real process with even a lower measured $\Delta T_{bath\text{-}HEXout}$ than calculated. Particularly experiences in designing and operating cryogenic facilities built the base for setting reasonably conservative boundary conditions in the design phase. The overall design of the process provides a good flexibility in terms of flow control including the two options of liquefaction into the LHe-bath. Also fluctuations originating from the refrigerator have to be taken into account.

4.2. Valve performance

As an example, Table 2 presents the required K_{vs}-values for the given input data and for compressible flow as obtained from the earlier described valve design sheet and the four cases for which the calculation was done. The results for incompressible flow vary to slightly larger K_{vs}-values for the example presented here. Based on the calculated values the valve was ordered with K_{vs} = 0.16. Figure 4 shows the calculated valve characteristics for compressible flow and Figure 5 the relevant measured data of this control valve during cryogenic operation.

Table 2. Example for valve design calculated for four cases of operation and compressible flow.

	Case 1	Case 2	Case 3	Case 4
Inlet pressure [bar]	4.0	4.5	3.5	6.0
Pressure loss [bar]	0.2	0.1	0.3	3.1
Mass flow [g/s]	2	3	1	4
Temperature [K]	5	5.5	4.5	300
K_{vs} required (compressible flow) [m³/h]	0.05	0.1	0.02	0.4

For the standard operation at 4.5 K the mass flow through the valve needs to be 2 g/s. The actual valve stroke was at 50% (see Figure 5 in the center (around “2. Jun 15”) the blue solid line for the mass flow and the blue dashed line for the stroke). Comparing this data with the design input values in Table 2 and the valve characteristics in Figure 4 these lie between case 1 and 3 which means a mass flow of 2 g/s should pass the valve at 50 to 60% stroke. A recalculation with the measured data yields a valve stroke of 58%.

Another comparison can be done for data at ambient temperatures as during cool-down or warm-up. The warm-up situation in Figure 5 (see on the right towards “10. Jun 15”) shows an actual mass flows of 0.3 g/s at 100% stroke. The design case 4 in Figure 4 gives 1.6 g/s through the fully opened valve. However, for the design of case 4 an inlet pressure of 6 bar, a critical flow (critical nozzle) and a temperature of 300 K was assumed (see Table 2). Recalculating case 4 with a pressure of 3 bar, a pressure drop of 0.3 bar (according measured data not presented in Figure 5) and a temperature of about 260 K a maximum mass flow of 0.55 g/s is predicted. Here it is essential to mention that after the valve follows a venturi pipe which represents the most constricted cross-section. Hence, especially at higher helium temperatures the control of the valve can be limited due to a critical flow through the venturi.

The good accordance of design calculation and measurement at cryogenic temperatures is very desirable since at these conditions the specific demands on process control for the experiment need to be fulfilled. On the other side it also has to be ensured that a reliable cool-down of the experiment is possible. The achieved cool-down and warm-up performance during tests was very sufficient.

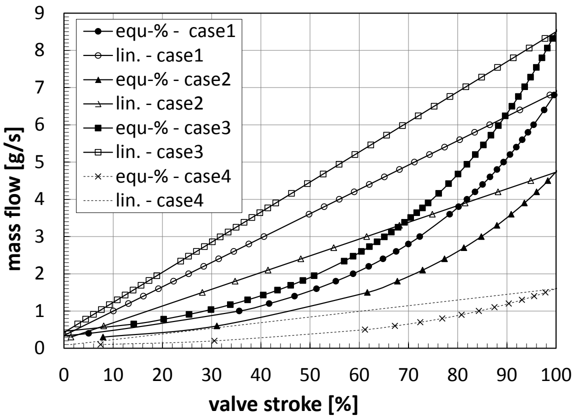

Figure 4. Calculated valve characteristics for compressible flow.

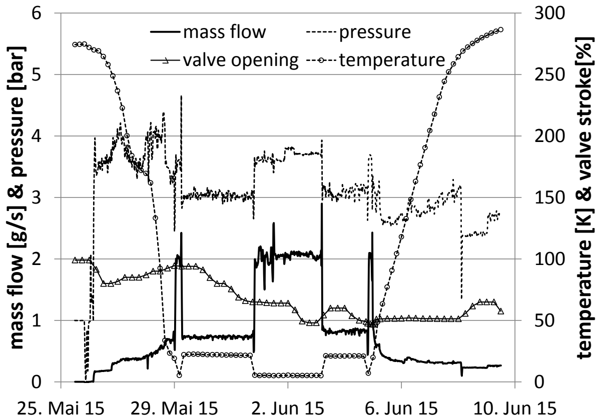

Figure 5. Measured data of a control valve with $K_{vs} = 0.16$.

5. Conclusion

The cryogenic current lead test facility CuLTKa was designed, built and commissioned in the KIT. The acceptance tests of 26 CL for the JT-60SA in Japan are in progress since 2014. The facility operates with helium at overcritical pressures at two different temperature levels, simultaneously.

Starting from given boundary conditions the paper sketches the setup of the whole facility. It consists of two valve boxes, one control box for temperature adjustments according the experimental demands and two test boxes. The cryogenic heart of the facility is a 400 l LHe-bath which is adjusting the inlet temperature of the 4.5 K-level via a cooling heat exchanger.

The whole cryogenic process design of the facility was done using in-house made engineering tools. Longtime experiences in designing and operating cryogenic facilities using forced-flow helium at overcritical pressures form an essential base. This helped to design the process with a sufficient flexibility as well as to apply reasonable safety margins. Generally it can be said that with the help of empirical engineering calculations such a cryogenic facility can be reasonably well designed. Also the design of parts like a pipe heat exchanger, the size of a LHe-bath or the design of cryogenic control valves can be done using such calculation tools. What is essential is a user-friendly access to fluid and material property data. The major benefit of using calculations based on Microsoft-Excel is its wide availability.

The evaluated data show some minor deviations from the calculated design data. However, keeping in mind that the applied calculations are no simulation and their aim is to design a functionally operating system with a rather small amount of effort in terms of time their benefit is obvious.

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