Load map of sumitomo 415DP cryocooler in the temperature range of 40-400K

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Abstract. In the last 20 years, 2-stage cryocoolers have been found to provide an optimum solution for a wide range of applications like low temperature physics, superconducting cold electronics, cryopumping and superconducting magnets. For a proper design of helium cryostats with significant cold masses connected to the first and second stages of cryocoolers, it is important to have a load map (also called “working field”) in order to estimate cool-down and warm-up time periods. Such load maps are either not presented in the open literature sources for “high” temperature ranges, or just given by manufacturing companies for general information but without any guarantee. In the present paper, the load map of a 2-stage Sumitomo 415DP cryocooler in the wide temperature range of 40-400 K is presented.

1. Introduction
Cryocoolers find wide application in low temperature physics, cryopumping, cold and superconducting electronics and superconducting magnets. They do not require permanent supervision during operation, have sufficiently long maintenance-free periods, have small space requirements and can be operated by personal without specialized education in cryogenics. Their main drawback is small cooling power of around 1.5-2 W @ 4.2 K (for 2-stage cryocoolers), which is still sufficient for many applications provided that cold masses and parasitic heat loads are low.

In the last 10-15 years, many applications have significantly higher cold masses, for example due to thermal radiation shields and superconducting magnets, where several cryocoolers are installed [1]. The cool-down or warm-up time will be in the range of days to weeks, which depends on the total amount of cryocoolers installed, and on the cold mass.

In order to properly estimate the cool-down and warm-up time (“time constants”) as well as validating that the target temperatures will be reached, it is important to have a load map (“working field”) of the used cryocooler. Such load maps can be found in the datasheet of the suppliers or in the open literature sources, for example in journals or conference proceedings [2] and [3]. However, not all datasheets have such load maps for all temperature ranges and in many cases, there are only a few performance points, which are guaranteed by manufacturers, for example for the cryocooler SRDK-415D with 1.5 W @ 4.2 K and 35 W @ 50 K for 50 Hz [4]. Journal and conference proceedings often do not provide sufficient detailed information, and attempts to estimate cooling power based on the scaling up (or down) of data from other cryocoolers is either not possible or imply large uncertainties [5]. For that reason, it is important to measure such load maps.

In the present paper, the load map of a 2-stage Sumitomo RDK-415DP with an air cooled compressor unit CAN-61D is presented. In section 2 of this paper, available data on the present
cryocooler model are summarized. The description of the set-up and test procedures is given in section 3, followed by the results in section 4. The measured data and further measurements are discussed in section 5.

2. Cryocooler parameters and load map

Table 1 summarizes the main parameters of the cryocooler used for the measurement of the load map [4].

Table 1: Main capacity and model parameters of the cryocooler for the measurement of the load map, taken from [4].

| Cold Head Unit | Model: RDK-415DP (with helium pot) |
|----------------|------------------------------------|
| Cooling capacity @ 50 Hz | 50 K @ 35 W |
| 1st stage | 4.2 K @ 1.4 W (in vertical position) |
| 2nd stage | Max. 15 % |
| Cooling capacity loss through orientation | Max. 5 % |
| Cooling capacity degradation within 10,000 Hrs | < 10 % |
| Cooling capacity loss through high ambient temperature (28 to 35 °C / 82.4 to 95°F) | Max. 5 % |
| Temperature fluctuation at Helium pot | Less than ± 50 mK @ 4.2 K |
| Compressor Unit (indoor and outdoor units) | Compressor Unit (indoor and outdoor units) |
| Cooling capacity loss through high ambient temperature (28 to 35 °C / 82.4 to 95°F) | CNA-61D (air cooled) |
| Static gas pressure | Max. 5 % |
| Power consumption @ steady state and 50 Hz | 16 – 17 bar (1.60 - 1.70 MPa) |
| Length of helium flexible line | 7.5 kW |
| Hours of operation after measuring the load map | 10 m |
| Hours of operation after measuring the load map | < 4,500 Hrs |

![Figure 1: Typical load map of an RDK-415D cryocooler operated with a 50 Hz compressor at high thermal loads on the second stage, taken from [6].](image_url)
The Load map, which is shown in Figure 1, is only valid for a limited temperature range of 2 - 20 K at second stage as well as 30 - 110 K at first stage and is served as reference only by the supplier. There are many dependencies which decreases cooling capacity and lead to different measured values of the load map. These dependencies can be summarized as follows:

- Usage of a Helium pot, the used model (Table 1) RDK-415DP (which is different from the available load map in Figure 1) is declared to reduce the cooling capacity due to the helium pot’s connecting capillary, which causes an additional heat load and reduces the cooling capacity to 1.4 W.
- Capacity losses due to cryocooler orientation (vertical, horizontal, inclined) can be up to 15 %, see [4].
- Capacity losses due to variation of ambient temperature (indoors and outdoors) can be 5% [4] for higher ambient temperatures no values are given (outside of the operation condition) [4].
- Capacity reduction due to degradation within the maintenance schedule (10,000 operating hours) is less than 10 %.
- Measurement equipment, i.e. position of sensors, anchoring and materials used for wiring is contributing to uncertainties.
- Shielding of the 2\textsuperscript{nd} stage influences thermal radiation and therewith contributes to the cooling capacity on both stages.

Due to the above mentioned points, measurement values can differ from the load map published by the supplier. When a broader temperature range of reliable values are needed and especially if several cryocoolers are interconnected, detailed information of the load map, should either be done through measurements in-house, or rely on data provided by other users.

3. In-house set-up and test procedure

3.1. Measurement set-up

Before the measurement cycle started, small modifications on the dewar have been conducted to reduce cold mass and to adjust the location of temperature sensors and heaters. The name and description of the installed instrumentation is shown in Table 2.

| No. | Name          | Calibration curve | Position and Type                                      |
|-----|---------------|-------------------|-------------------------------------------------------|
| 1   | Heater-1      | -                 | First stage, on the thermal radiation shield          |
| 2   | Heater-2      | -                 | Second stage, on the copper block                     |
| 3   | T1            | Standard curve    | On the 2\textsuperscript{nd} stage, Si1              |
| 4   | T2            | Standard curve    | On the 2\textsuperscript{nd} stage, Si2              |
| 5   | T3            | Standard curve    | On the copper block, near the heater on the 2\textsuperscript{nd} stage, Si3 |
| 6   | T6            | Standard curve    | Shield, Pt100                                        |
| 7   | T5            | Standard curve    | Shield, Pt100                                        |
| 8   | T4            | Standard curve    | Shield, Pt100                                        |

To reduce cold mass, a mounting plate for experiments 0.5 m (diameter) on the 2\textsuperscript{nd} stage has been dismounted. Thereby mounted temperature sensors, heaters and wiring have been adjusted. Figure 2 and Figure 3 shows the position of instrumentation within the in-house set up.
Figure 2: On the left, the open dewar with the lower part of the radiation shield and the dismounted experimental plate on the 2nd stage. On the right, the heater for the 1st stage and temperature sensor T6 can be seen.

In the calculations a parasitic thermal conduction over very thin and long G10 rods as well as measuring wires could be practically neglected, so the only significant contribution will be due to thermal radiation. The final decision to conduct most of the measurements with “large” radiation shield was done due to the following reasons:

- Present surface treatment, which was chosen for experiments with radio frequency ranges, had quite low emissivity coefficient, which led to sufficiently low heat load on the first stage.
- According to an experience of one of the co-authors, an application of superinsulation with large number of layers typically leads to a large scattering of measurement points (i.e. statistical error). This effect is not sufficiently good investigated but according to our suspicion, it could be caused either by a residual gas between superinsulating layers or by different thermal conductivity of superinsulation due to mechanical and thermal contacts of adjacent layers (so it could be that from cool-down to cool-down, number of contacting points is different and therefore thermal conduction is also different).
- Due to small thermal parasitic heat load and advantage of good reproducibility of measurements for the case without superinsulating, it was decided to perform all measurements at the present configuration. The estimations of radiation heat load was done with experimental set-up with small radiation heat load, see Figure 5 for experiments with a small radiation shield, and correction of the heat load on the first stage could be done according to the formula $Q(T) = 40 * (300^4 - T^4) / (300^4 - 48^4)$.
Figure 3: On the left, the position of T1 and T2 on the 2nd stage. On the right, the installation of the electrical heater and temperature sensor T3 on the 2nd stage is shown.

For the temperature measurement on the first stage, glass-encapsulated Pt100 were used. This choice was offered by manufacturing company of the cryostat due to low costs as well as very good long-term stability, i.e. water penetration between Pt-wire and glass housing with additional of parasitic resistance to ground could be practically excluded. These sensors were inserted inside the hole of small copper blocks, which were further screwed to the radiation shield. In order to improve thermal contact between glass and copper block, Apiezon grease was used. The slot between copper block and sensor was kept as low as possible in order to reduce the temperature difference over the grease (manufacturing company had long-term positive experience with these sensor installation).

All wires installed to the dewar have been thermally anchored to either both stages or the first stage. Copper bobbins have been used for thermal anchoring. For temperature sensors, phosphor bronze wires have been used to further reduce the parasitic heat load.

For the temperature cross-check and for temperature calibration in the range of 50-70 K, other sensors were used. From these measurements it was found that temperature uncertainties of Pt100 could be estimated as ±3 K (2σ confidence interval). The temperature cross-check of Si-diodes (LakeShore Cryotronics), showed a deviation of ±0.3 K (2σ) at low temperature, which increased up to ±0.6 K (2σ) at 300 K. For the temperature monitoring and heater operation, two different devices were used, i.e. LakeShore 224 Temperature Monitor and TIC 500 Controller from CryoVac.

The cartridge heaters (HTR-25-100 according to LakeShore Cryotronics notation) were applied. In order to operate heaters with high heat loads on the first and second stage, the wires with larger cross-sectional areas (otherwise they could be “burnt” in vacuum) have to be used. Moreover, in order to avoid any contact between heater and sensor wires (otherwise, sensor wires could be burnt) we had to separate them at the largest possible distances. For that reason, some of the cables were additionally “fixed” with tapes on mechanical parts. The aluminum thermal radiation shield with a surface area of around 1 m² and without superinsulation was applied. The surface of the radiation shield (inside and outside) has been passivated to obtain required electrical properties for future high frequency operations.

In order to have negligible effects of the heat transfer due to residual gas, the insulation vacuum was kept below 10⁻⁴ mbar.

3.2. Measurement procedure

Measurements were performed from July to November 2018. Initial to the measurement procedure both heaters have been switched off to approach equilibrium at lowest possible temperature for the measurement setup (around 48 K @ 1st stage and 2.9 K @ 2nd stage). These temperature baselines for 0 W @ 1st stage and 0 W @ 2nd stage have been used to cross check the measurement setup over time.
Then the measurement procedure continued as follows:

1. Increase of heating power on the 1\textsuperscript{st} stage (0 W, 15 W, 20 W, 30 W, 40 W, 50 W, 60 W, 70 W, 100 W and 200 W). The heating power on the 2\textsuperscript{nd} stage was held constant.
2. Before the heating power on the 2\textsuperscript{nd} stage was increased and a new measurement cycle started both heaters have been switched off to approach the temperature baselines 0 W @ 1\textsuperscript{st} stage and 0 W @ 2\textsuperscript{nd} stage to cross check the measurement set up.
3. Increase of heating power on the 2\textsuperscript{nd} stage (0 W, 20 W, 30 W, 40 W and 50 W). Once setting the heating power on the second stage the measurement cycle continued on point 1.

In order to check the reproducibility of the data, some measurement points were repeated at different conditions, e.g. by decreasing of heating powers on the first and second stages or measurement after a “long” (around 1 week) stand-by at room temperature.

The steady-state temperature conditions were measured at least for 3 hours and in some cases up to one week. The temperature variation was typically less than 0.5 K.

4. Results

Figure 4 shows the measured load map of the SRDK-415DP-A61D cryocooler in the temperature range of 40 – 350 K for the first stage and 2.9 – 400 K for the second stage.

![Figure 4: The measured load map of the SRDK-415DP-A61D cryocooler.](image-url)
Table 3: The heating power of both stages and the measured temperatures.

| 1st stage Power (W) | 2nd stage Power (W) | 1st stage Temperature (K) | 2nd stage Temperature (K) | 1st stage Power (W) | 2nd stage Power (W) | 1st stage Temperature (K) | 2nd stage Temperature (K) |
|---------------------|---------------------|---------------------------|---------------------------|---------------------|---------------------|---------------------------|---------------------------|
| 0                   | 0                   | 46                        | 2.7                       | 0                   | 30                  | 48                        | 48.9                      |
| 0                   | 0                   | 49                        | 2.8                       | 15                  | 30                  | 59                        | 46.2                      |
| 0                   | 0                   | 47                        | 3.3                       | 20                  | 30                  | 64                        | 46.0                      |
| 0                   | 0                   | 49                        | 3.0                       | 30                  | 30                  | 78                        | 47.1                      |
| 0                   | 0                   | 47                        | 2.9                       | 40                  | 30                  | 96                        | 50.6                      |
| 0                   | 0                   | 48                        | 2.6                       | 50                  | 30                  | 117                       | 58.0                      |
| 15                  | 0                   | 61                        | 2.8                       | 60                  | 30                  | 135                       | 64.8                      |
| 20                  | 0                   | 74                        | 3.0                       | 70                  | 30                  | 156                       | 77.3                      |
| 30                  | 0                   | 94                        | 4.4                       | 100                 | 30                  | 202                       | 108.0                     |
| 40                  | 0                   | 117                       | 5.7                       | 200                 | 30                  | 321                       | 297.7                     |
| 50                  | 0                   | 144                       | 7.8                       | 0                   | 40                  | 49                        | 136.6                     |
| 60                  | 0                   | 157                       | 10.0                      | 15                  | 40                  | 60                        | 128.7                     |
| 70                  | 0                   | 171                       | 12.1                      | 20                  | 40                  | 66                        | 126.4                     |
| 100                 | 0                   | 206                       | 16.7                      | 30                  | 40                  | 79                        | 124.1                     |
| 200                 | 0                   | 301                       | 107.9                     | 40                  | 40                  | 96                        | 125.5                     |
|                     | 0                   | 20                        | 58                        | 50                  | 40                  | 116                       | 130.7                     |
|                     | 15                  | 20                        | 74                        | 60                  | 40                  | 137                       | 139.2                     |
|                     | 20                  | 20                        | 80                        | 70                  | 40                  | 157                       | 154.8                     |
|                     | 30                  | 20                        | 95                        | 100                 | 40                  | 211                       | 193.0                     |
|                     | 40                  | 20                        | 115                       | 200                 | 40                  | 333                       | 344.8                     |
|                     | 50                  | 20                        | 134                       | 0                   | 50                  | 53                        | 235.5                     |
|                     | 60                  | 20                        | 137                       | 15                  | 50                  | 66                        | 229.1                     |
|                     | 70                  | 20                        | 154                       | 20                  | 50                  | 74                        | 228.9                     |
|                     | 100                 | 20                        | 206                       | 30                  | 50                  | 94                        | 230.0                     |
|                     | 200                 | 20                        | 308                       | 40                  | 50                  | 110                       | 231.3                     |
|                     |                     |                            |                            | 50                  | 50                  | 128                       | 234.8                     |
|                     |                     |                            |                            | 70                  | 50                  | 178                       | 250.6                     |
|                     |                     |                            |                            | 100                 | 50                  | 236                       | 285.0                     |
|                     |                     |                            |                            | 200                 | 50                  | 346                       | 396.7                     |
|                     |                     |                            |                            | 70                  | 60                  | 185                       | 298.6                     |
|                     |                     |                            |                            | 100                 | 60                  | 261                       | 357.2                     |
|                     |                     |                            |                            | 70                  | 70                  | 208                       | 348.4                     |

Figure 5: Thermal radiation shield mounted on the first stage of Sumitomo Cryocooler and used for the cross-check of the thermal radiation heat load.
5. Discussion
A high (“parasitic”) heat load of around 40 ± 5 W (2σ) has been estimated from the difference between data shown in Figure 1 and the measured values from Figure 4 (1st stage temperatures). For the cross-check of this heat load, a smaller copper shield has been built with the result that the heat load reduced from 40 W to around 13 W (operation with single reflective aluminum foil and several measurement points at different temperature levels were taken), see Figure 5. This large “parasitic” heat load led to a “shifting” of the measurement data for the first stage as well as contributed to the large uncertainties of the heat load measurement of this stage. So, it is possible to make correction to the first stage heat load by subtracting the thermal radiation heat load according to the formula:

\[ Q(T) = 40 \times (300^4 - T^4)/(300^4 - 48^4) \]

A temperature deviation of 3 K in a period of 24 hours could be monitored with 0 W heat loads on 1st stage.

6. Conclusion
In the present paper the working field of the Sumitomo SRDK-415DP-A61D cryocooler in the range of 40 – 350 K for the 1st stage and 3 – 400 K for the 2nd stage is presented (0 W – 200 W @ 1st stage and 0 W – 50 W @ 2nd stage).

It could be figured out that measured points do not significantly depend on cooling down or warming up (“hysteresis”), but on the ambient conditions. For further measurements related to the improvement of reproducibility, it would be better to choose a water cooled compressor. In this case, the ambient temperature will have smaller effect on the helium temperature, which is supplied from compressor to the cold head.

It is worth to note that within the present set-up it is not possible to measure the dynamic response of the cryocooler [7]. This is related to the fact that large masses with significant heat capacities are connected to the first and the second stages (i.e. copper braids).

7. References
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