IOP Conf. Series: Materials Science and Engineering **1344** (2026) 012105 doi:10.1088/1757-899X/1344/1/012105

Parametric thermal characterization of Sumitomo RDE-418D4 two-stage Gifford-McMahon cryocooler

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Abstract. Our application seeks cryorefrigeration in liquid neon and liquid helium temperature range. For this purpose, the highest capacity 4K two-stage Giffard-McMohan cryocooler manufactured by Sumitomo (SHI) Cryogenics Group has been employed. At second-stage temperature of 4.2 K, the coldhead RDE-418D4 has refrigeration capacity specifications of 1.8 W @ 50 Hz and 2.0 W @ 60 Hz with first-stage load of 42 W and 50 W respectively. It is operated with F-50SH water-cooled helium compressor embedded with coldhead frequency inverter. This work presents the thermal characterization of the cryocooler second-stage at varying heat loads from 100 mW to 25 W. Different data sets are obtained while maintaining the first stage at no heat load (0W) or under constant heat load conditions (25 W, 50 W, 75 W). Additionally, the cooling capacity data is recorded at different coldhead operating frequency of 40 Hz, 50 Hz, 60 Hz and 70 Hz.

1. Introduction

Cryocoolers are an excellent go-to solutions when cryogen-free dry cooling is essential [1]. The existing cryocoolers in the market are certified with the cooling capacity specified only at generic points (such as 4.2 K, 10 K and 20 K) [2]. However, if the cryorefrigeration is to be obtained in any other cryogenic temperature range, the cryocooler capacity is not readily available. It is indeed possible to get a rough estimate from the capacity map supplied with the cryocoolers. Nevertheless, this is a generalized data based on tests conducted on numerous cryocoolers and not specific to the cryocooler unboxed.

One of the current objectives of our laboratory is to build a test set-up demonstrating conduction cooling of a superconducting magnet by a single two-stage cryocooler utilizing two cryogenic pulsating heat pipes (PHP) as thermal links. The operational temperature of the magnet requires it to be maintained in the range of 30–35 K which is why neon is chosen as the PHP working fluid. The PHP consists of three parts – the condenser, the evaporator and the adiabatic part [3, 4]. The PHP condenser will host the cryocooler as the cold source while the heat generated by the magnet will be dumped on the PHP evaporator. Two-phase oscillatory motion of the liquid plugs and vapour bubbles within the adiabatic part will facilitate transport of heat received at the evaporator to the cryocooler [3, 4].

In view of this application, it is therefore primarily essential to quantify the cooling capacity of cryocooler second-stage in priori between 24.5 K (neon freezing temperature) to 35 K temperature range. Anticipating future uses of this cryocooler with other cryogens as well, a

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parametric characterization of the cryocooler has been conducted between the lowest temperature that the cryocooler second stage can reach and upto 35 K.

Additionally, while working with cryogenic temperatures, heat in-leak by radiation from the room temperature must be intercepted. Current leads of the magnet are a huge source of conductive heat loads along with Joule heating that amount in order of several watts. In case of a two-stage cryocooler, the first stage is used to intercept these heat loads. It is, therefore, vital to know the variation in second-stage cooling capacity under different heat load at first stage.

The third parameter investigated is the operating frequency of the coldhead. The compressor electrical input of 50 Hz given by the main power remains constant. As per the manufacturer's specifications, it is possible to obtain higher cooling capacity at higher coldhead operating frequency as more helium flows through the coldhead. Particularly for very low cryogenic temperatures, few milliwatts of extra power can be significant importance. As a result, performance of the cryocooler at four frequencies is also recorded.

The cryocooler specifications, details of the experimental set-up and the obtained characterization curves have been given in the sections that follow.

2. Cryocooler coldhead and compressor specifications

The specifications of Sumitomo-make 4K coldhead *RDE-418D4* and water cooled (high voltage) compressor unit *F-50SH* have been briefly tabulated in Table 1 and Table 2 respectively. Detailed description can be found through resources provided by Sumitomo in [5, 6].

Table 1. Sumitomo-make 4K coldhead RDE-418D4 specifications [5].

	50 Hz	60 Hz
2nd stage capacity	1.8 W @ 4.2 K	2.0 W @ 4.2 K
1st stage capacity	42 W @ 50 K	50 W @ 50 K
Minimum temperature	<3.5 K	<3.5 K

Table 2. Sumitomo-make water cooled (high voltage) compressor unit *F-50SH* [6].

	50 Hz	60 Hz
Electrical Supply	3 Phase 380/400/415 V	3 Phase 460-480 V
Power consumption	6.5-7.2 kW	7.5-8.3 kW
Cooling water inlet mass flow rate	7-10 L/min 4-28 °C	7-10 L/min 4-28 °C
	*Inverter-controller	

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3. Test Facility

In order to conduct the cryocooler performance tests, the experimental set-up is built as per the schematic shown in Figure 1. The cryocooler coldhead is placed on top of a cryostat flange. An aluminium radiation shield is attached on the first stage to intercept radiation heat load coming directly from the cryostat to the first stage. Additionally, 15 layers of superinsulation are enclosed around the shield at first stage as well as the copper part of the second stage.

Two Cernox® thin-film resistance cryogenic temperature sensors measure the temperature of the first and second stage of the cryocooler. The in-built sensor hole in the second stage is slightly enlarged to precisely fit the CX-1050-AA type of sensor. On the first stage, for the same type of sensor, a hole is drilled within the shield flange close to the first stage copper part. A PT-100 temperature sensor is also mounted on the stainless steel mandrel between the coldhead and the first stage as depicted in Figure 1.

Heat load on the second stage is imposed by a Kapton™ thermofoil™ heater glued on it while on the first stage two Dale chassis mount resistor heaters are attached on the shield flange diametrically opposite to one another. A cryogenic temperature controller CTC100 reads the temperature sensors as well as regulates the power supply to the heaters. A LabVIEW program records the temperature and heat load variation. Additionally, another LabVIEW program is designed to control the compressor start-stop, coldhead operating frequency and monitor the operational parameters.

Prior to the start of the cryocooler, a vacuum in the order of 10^{-4} mbar is achieved by the rotary and turbo-molecular pump. As the temperature descends with the cryocooler, vacuum ranges in 10^{-7} mbar during the tests.

The parasitic heat load due to radiation on the first and second stage is about 1.12 W and 0.5 mW respectively. The heat load through instrumentation wiring due to conduction and Joule effect is 0.55 W on first stage and 35 mW on second stage.

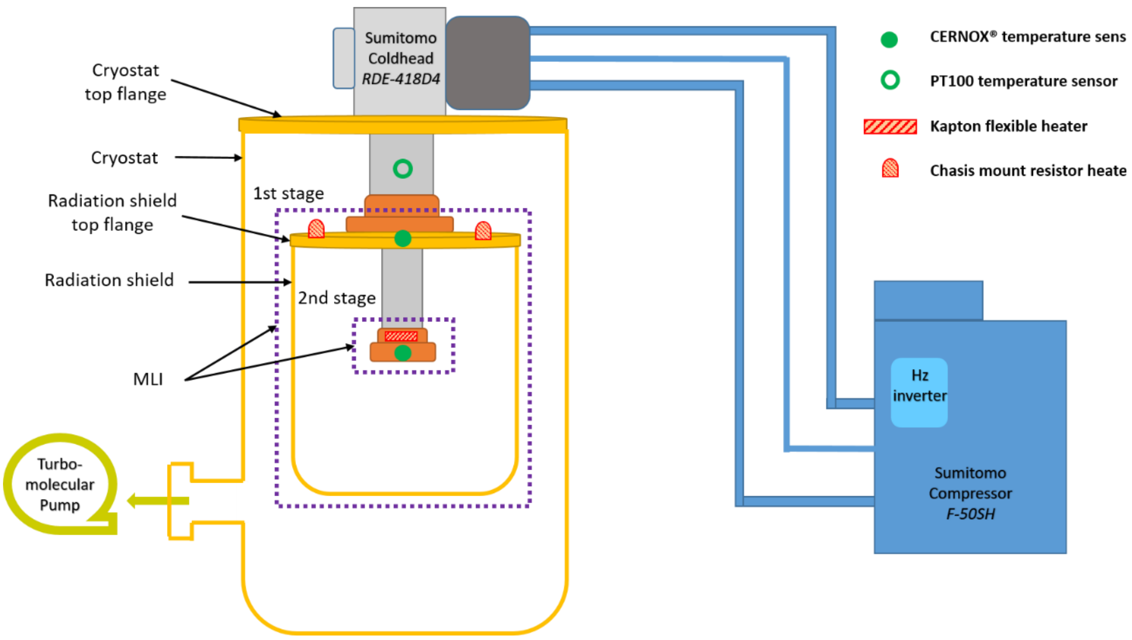

Figure 1. Schematic of cryocooler test facility.

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4. Characterization Curves

The cryocooler second stage is extensively characterized at several data points for 50 Hz and 60 Hz with no heat load and 50 W at first stage. For all other parametric variation, the data is primarily noted at three points – 4.2 K, 20 K and 27 K corresponding to liquid helium, liquid hydrogen and liquid neon at 1 atmospheric pressure. Same set of tests have been conducted on different days to confirm repeatability. In the first cooldown – recorded at 50 Hz and no heat load on the first stage – the cryocooler second stage is observed to reach the lowest temperature of 2.297 K. Figure 2 to Figure 6 graphically present the different characterization curves recorded. The heat load refers to the power imposed with the heaters. Parasitic heat loads specified in section 3 must be additionally accounted for. The temperature of the mandrel between the coldhead and the first stage is recorded in the range of 221 K to 238 K for 50 Hz and 60 Hz at 0 W and 247 K to 253 K for same frequencies at 50 W. For the highest frequency and heat load tested (70 Hz and 75 W), temperature of ~262 K is seen at the mandrel while the second stage is at 4.2 K.

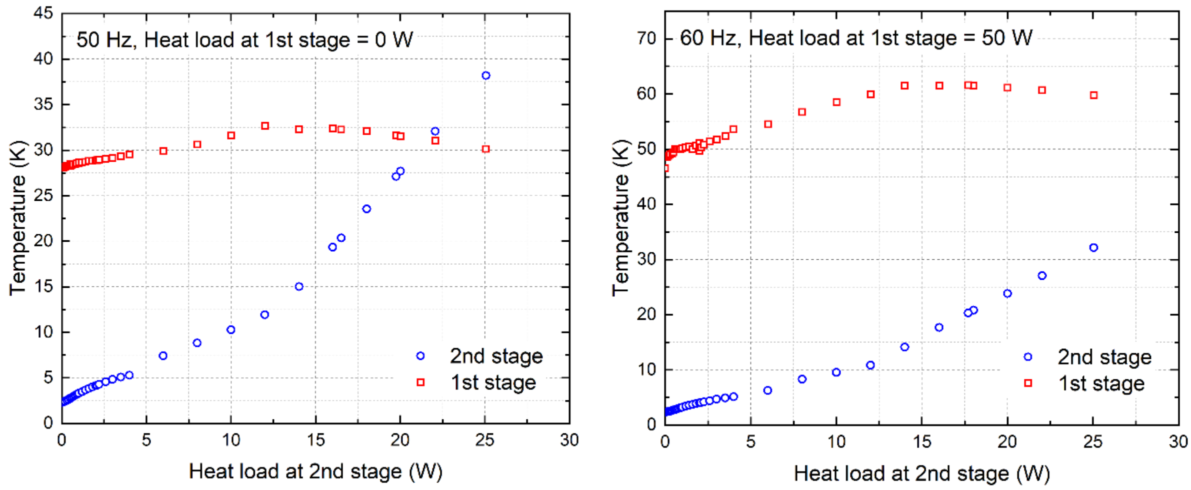

Figure 2: Temperature variation of cryocooler stages with variation in heat load of second stage at coldhead operating frequency of 50 Hz with 0 W and 50 W heat load at first stage

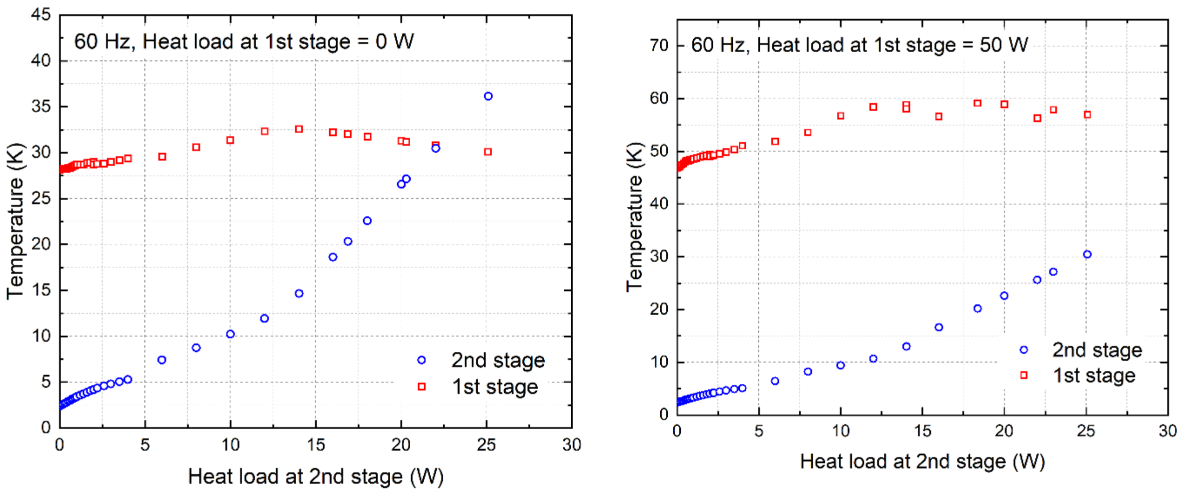

Figure 3: Temperature variation of cryocooler stages with variation in heat load of second stage at coldhead operating frequency of 60 Hz with 0 W and 50 W heat load at first stage

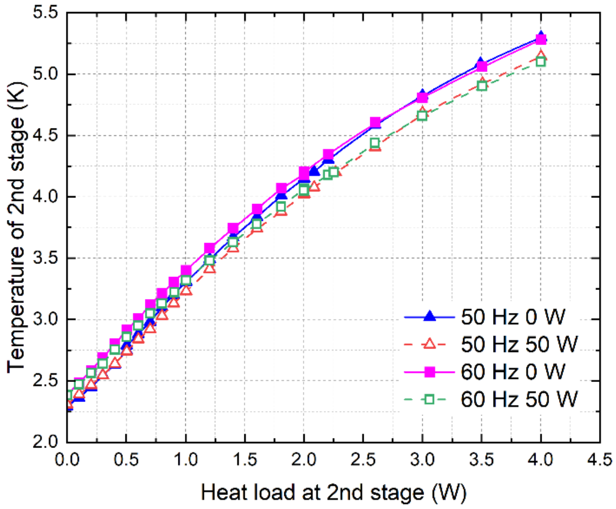

Figure 4: Magnified view of cryocooler performance data for second stage temperature ranging between 2.3 K and 5.5 K at coldhead operating frequency of 50 Hz and 60 Hz and 0 W and 50 W first stage heat load

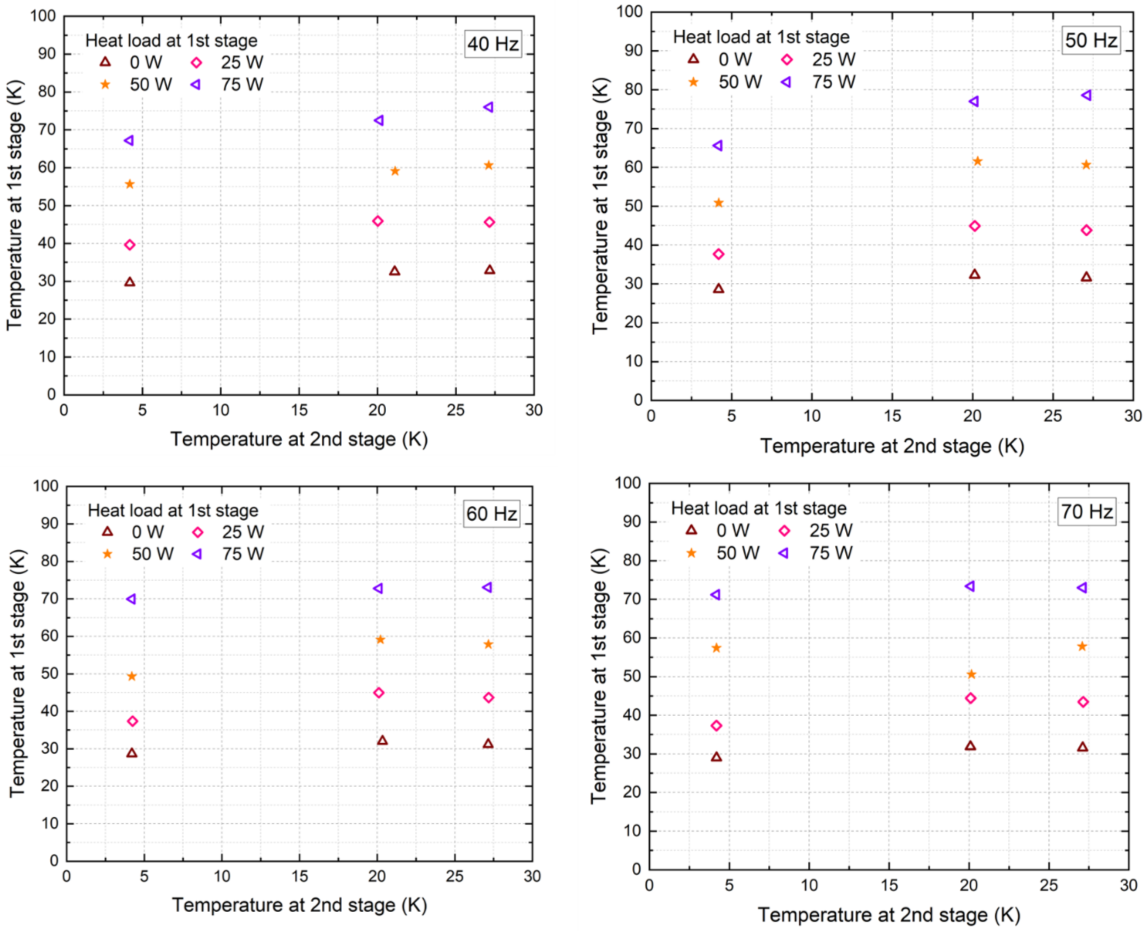

Figure 5: Temperature variation of first stage against that of second stage (at 4.2 K, 20 K and 27 K) with increasing heat load on first stage (0 W, 25 W, 50 W, 75 W) and different coldhead operating frequencies (40 Hz, 50 Hz, 60 Hz, 70 Hz)

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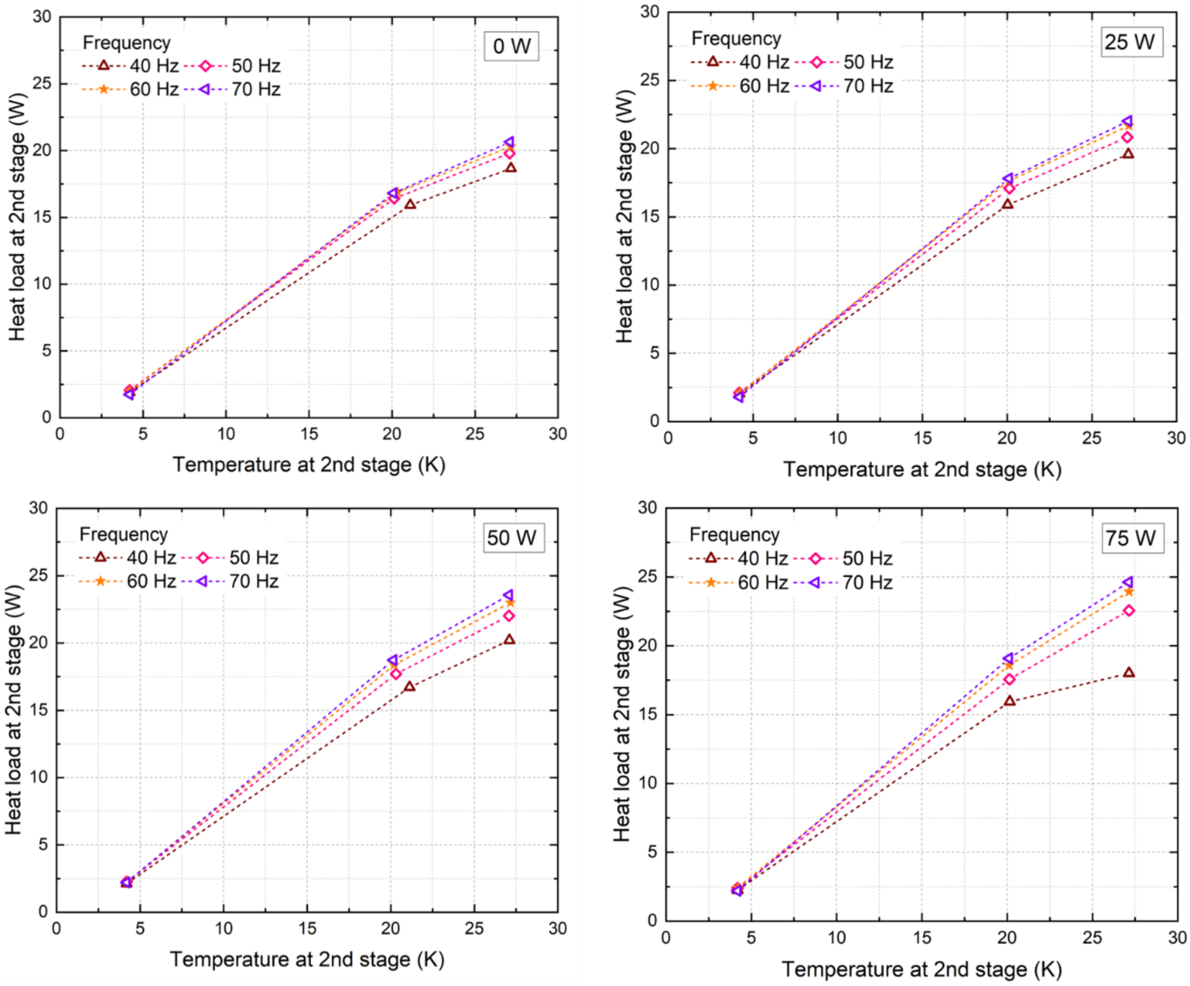

Figure 6: Heat load variation of second stage against its temperature (at 4.2 K, 20 K and 27 K) with increasing coldhead operating frequency (40 Hz, 50 Hz, 60 Hz, 70 Hz) and different heat load on first stage (0 W, 25 W, 50 W, 75 W)

Some of the distinct observations made based on the obtained characterization plots of the Sumitomo cryocooler *RDE-418D4* operated with *F50-SH* helium compressor are as follows:

- This coldhead performs superior than the manufacturer's specifications at 4.2 K for 50 Hz with second stage cooling capacity of 2.08 W (instead of 1.8 W). For 60 Hz, same value as specified by the manufacturer is recorded (2 W).
- Under no heat load at first stage and second stage cooling capacity above ~22 W, the second stage temperature is seen to surpass the temperature of first stage.
- Larger the heat load on the first stage, higher is its temperature. For example, at 50 Hz frequency and 50 W heat load, increase in the first stage temperature is 20 – 30 K higher than under no load condition.
- Higher the coldhead operating frequency, higher is the second stage cooling capacity with increasing temperature.

Acknowledgments

The authors thank Sumitomo for letting them publish this data. Purchase of the cryocooler is supported by the Agence National de la Recherche (ANR) under the Program d'Investissements d'Avenir (Future Investment Program) with the reference Grant No. PACIFICS ANR-21-ESRE-0049 program.

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