The Latest Developments in Low-Cost, Low-Power Cooling to below 1 Kelvin

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ABSTRACT

Self-contained, sealed ^{4}He sorption modules, interfaced to low-power mechanical precoolers, provide simple, reliable and economical access to temperatures below 1 K. The technology for low-power sub-Kelvin cooling is well established and available products offer fully automated operation, require no special supporting infrastructure and little or no cryogenics expertise. In this paper, we present breaking developments with the very latest products of this type.

Chase Research Cryogenics' (CRC) compact GL4 modules are designed to interface to the Sumitomo RDK101 cold head, run from a CNA-11 compressor, which is air-cooled, utilises single-phase electricity, and is small enough to fit under a desk or even into a 19-inch rack. A medium-sized GL4 module runs at a base temperature of approximately 800 mK and typically provides around 40 hours run time under a 100 μW applied load [1].

We are testing a new design of GL4 which incorporates many improvements to give a more consistent performance. We also compare and contrast the performance obtained using the RDK101 cold head with a new cold head in development by Sumitomo, the 2KGM. This new cold head, an evaluation version which has kindly been made available to us by Sumitomo, is even smaller than the RDK101. It has superior cooling power to the RDK101 at the second stage, and hence reaches a lower operating temperature, while still using the compact CNA-11 compressor.

Our results clearly demonstrate that the lower temperature of the 2KGM produces a significantly better performance from our GL4 modules, enabling longer run times and greater heat lifts. Operational characteristics such as cooldown time and GL4 recycling time are the same for both RDK101 and 2KGM. The new medium-sized GL4 provides a run time of around 45 hours when operated under a 100 μW applied load with the RDK101/CNA-11 combo, but the 2KGM further improves the new GL4's performance under all load conditions.

INTRODUCTION

In this paper, we present results from testing a new generation of GL4 module, incorporating design and manufacturing improvements to give more consistent performance. Like our existing GL4, the new module is designed to interface to a Sumitomo RDK101 cold head. We compare the early results for this new module with the extensive performance data we have for our current production version of the GL4 (see reference list), and we assess the merit of the changes made.

We also compare and contrast the GL4's performance when using different GM cryocoolers to precool the GL4 module. We have evaluated the performance of our new GL4 module with three

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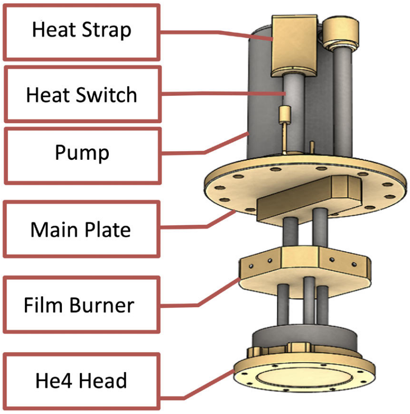

Figure 1. Schematic diagram of a GL4 sorption module.

different cold head/ compressor combinations that are the Sumitomo RDK101 with CNA-11 compressor, Sumitomo RDK101 with Zephyr compressor and Sumitomo 2KGM with CNA-11 compressor.

The 2KGM cold head is a new technology in development by SHI Cryogenics. It is considerably shorter than the RDK101. It has superior cooling power to the RDK10I at the second stage, and hence reaches a lower operating temperature than the RDK101. The 2KGM utilises the same compact CNA-11 compressor as the RDK101. An evaluation version of the 2KGM was made available to us by SHI Cryogenics for the purposes of this study.

HOW THE GL4 MODULE WORKS

The GL4 module, shown schematically in Fig.1, contains helium 4 (^{4}He) gas. When running, the module is oriented with the head at the bottom allowing liquid helium to collect under gravity in the head. The pump contains charcoal onto which the ^{4}He gas is adsorbed. The main plate is interfaced to the 4 K cold head of the GM cryocooler, which cools the module below the liquefaction point of ^{4}He. The film burner incorporates a small, sharp-edged orifice to prevent superfluid liquid ^{4}He from creeping from the head up the connecting tube. The gas-gap heat switch connects the pump to the main plate via a heat strap.

To run the module, the pump is warmed by applying a voltage to its heater. This drives off the ^{4}He gas from the charcoal. Helium then condenses to liquid at the main plate and collects in the head. When all of the helium has condensed, the pump is cooled by turning its heater off and turning on the heat switch. The heat from the pump is quickly dumped into the main plate. This reduces the vapour pressure inside the module.

The liquid helium in the head now starts to evaporate, and due to the latent heat of vaporization the head cools to ~800 mk. The module stays at this temperature until all the liquid helium has evaporated and the gas is once again adsorbed into the pump. The module can now be recycled by turning the heat switch off and warming the pump to start the cycle over again.

EXPERIMENTAL METHODS

Five new-design GL4 modules were run with three different GM/compressor combinations. Each module was run at least twice under different applied load conditions. During each run we logged the temperature versus time, using generic ruthenium oxide sensors on the GL4 cold head and main plate, which is thermally interfaced to the second stage of the GM cryocooler. We used generic silicon diode sensors to monitor the temperatures of the film burner, pump, heat switch and the first stage of the GM cryocooler. Temperatures were logged using Lakeshore Cryotronics temperature monitors and are accurate to ±0.1 K with the generic RuO2 sensors and generic calibration tables used.

Figure 2. GL4 module interfaced to the GM cold head.

Known loads were applied to the cold head of the GL4 using a precision resistor and programmable power supply. The GL4 control, temperature monitoring and loading sequences were fully automated using a Labview interface to the instruments utilized.

The cryostat used for the tests has an aluminium vacuum jacket 25 cm in diameter and 65 cm long. The GM cold head and low-dissipation wiring lead-ins are inserted through hermetic seals on the aluminium top plate. The outer vacuum jacket houses two inner radiation shields. The 40 K radiation shield (measuring 23 cm in diameter and 50 cm long) is made from thin-wall aluminium, covered (for later tests only) in 10 layers of MLI on the top, bottom and sides. The 40 K shield is thermally interfaced to the first stage of the GM cryocooler. The inner 4 K radiation shield, also made from thin-wall aluminium, is thermally interfaced to the second GM stage. It measured 20 cm in diameter, 30 cm long, and had no MLI.

Fig. 2 below shows the GL4 module interfaced to the GM cold head, below the top plate of the cryostat and the first stage of the GM.

It can be seen that the main plate of the GL4 module is bolted directly to the cold head of the Sumitomo GM. The cold head of the GL4 module sits inside the 4 K radiation shield, and the pump of the GL4 module, which during cycling is heated to 40-50 K, sits within the 40 K radiation shield between the first and second stages of the GM

RESULTS

In Table 1 we present temperature data for the GM cold head in different experimental runs. In early runs the temperature of the second stage was not logged, but having observed it to be higher

Table 1. GM temperature data.

Cold Head	Compressor	Second stage (K)	First stage (K)	40K Radshield
RDK101	CNA-11	2.79		No MLI
RDK101	CNA-11	2.89		No MLI
RDK101	CNA-11	2.69		No MLI
RDK101	CNA-11	2.84	45	No MLI
2KGM	CNA-11	2.32		No MLI
2KGM	CNA-11	2.34		No MLI
2KGM	CNA-11	2.34		No MLI
2KGM	CNA-11	2.43	60	No MLI
2KGM	CNA-11	2.65	60	No MLI
RDK101	CNA-11	2.45	44	MLI added
2KGM	CNA-11	2.48	42	MLI added
2KGM	CNA-11	2.64	41	MLI added
2KGM	CNA-11	2.28	43	MLI added
RDK101	Zephyr	2.44	26	MLI added
RDK101	Zephyr	2.24	26	MLI added

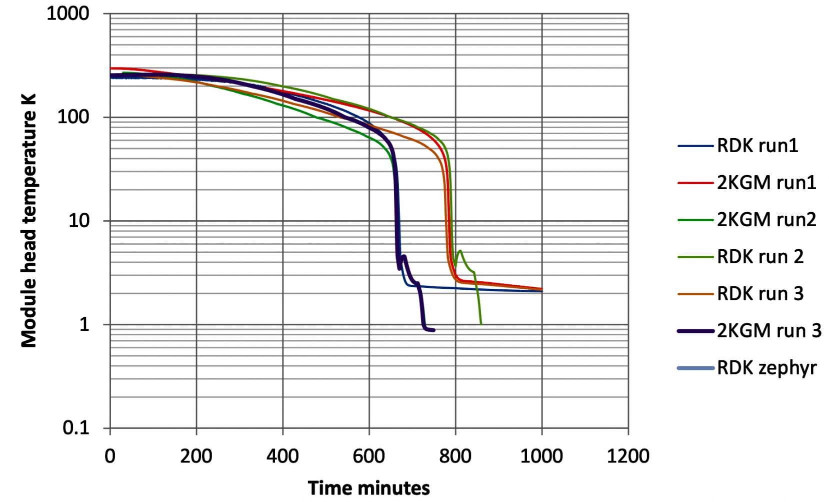

Figure 3. Cooldown of the cryostat and GL4 module from room temperature to below 4 K, for different GM / compressor combinations.

than expected, a multilayer insulation wrap was later added to the top, bottom and sides of the 40 K radiation shield. This significantly reduced the temperature of the first stage, but had no measurable effect on the temperature of the second stage.

The time taken for the entire system to cool down from room temperature to below 4 K is in the range 10-12 hours. There is no systematic difference in cooldown time between the RDK101 and the 2KGM cold heads, see examples of data given in Fig. 3.

In Table 2 we summarize the data from tests with five GL4 modules, run with three different GM/compressor combinations. For purposes of comparison, data from a single run using a 'wet' cryostat with pre-cooling by liquid ^{4}He are also included.

Variations in the temperatures of the heads of the GL4 modules when running under zero applied load (zero load temperature) are not significant given the measurement uncertainty of the sensors used. The measured run time of the modules is strongly dependent on the average load applied to the head while it is running.

The plot of run time versus applied load, in Fig. 4, shows that for a given average loading the RDK101/CNA11 gives a shorter run time than either the 2KGM/CNA11 or the RDK101/Zephyr. The 'wet' cryogen pre-cooling gives a significantly lower run time than any of the GM systems.

Table 2. GL4 module data.

Cold Head	Compressor	Module ID	Zero load temperature K	Total Applied Load mJ	Average load µW	Measured run time hours
2KGM	CNA-11	#050620	0.82	0	0.0	69.50
2KGM	CNA-11	#050620	0.81	15336	103.0	41.34
2KGM	CNA-11	#090620	0.79	20106	99.9	55.92
2KGM	CNA-11	#090620	0.79	27376	357.6	21.26
2KGM	CNA-11	#040620	0.87	27932	358.4	21.65
2KGM	CNA-11	#100620	0.88	28039	358.5	21.723
RDK	CNA-11	#040620	0.86	15056	99.5	42.05
RDK	CNA-11	#090620	0.81	16924	99.5	47.24
RDK	CNA-11	#090620	0.81	21281	347.1	17.03
RDK	CNA-11	#040620	0.86	22343	349.3	17.77
RDK	CNA-11	#050620	0.77	26336	356.9	20.50
RDK	Zephyr	#100620	0.74	19985	98.2	56.52
RDK	Zephyr	#100620	0.83	27578	358.6	21.36
RDK	Zephyr	#300920	0.90	28056	364.3	21.39
Wet L4He	n/a	#040620	0.90	9191	99.1	25.76

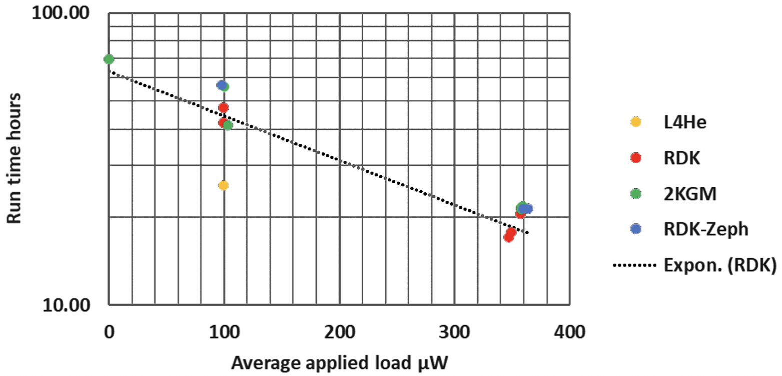

Figure 4. The relationship between run time and average applied load during the run.

The run times for the new GL4 module are within the range of those obtained with our existing standard medium-sized GL4 module [2]. Previous results from testing 20 different medium-size standard GL4 modules showed average run times of 40 ±8 hours for ~100 µW average applied load and 20 ±3.7 hours for ~350 µW average applied load (mean ±1 standard deviation). The variability of these previous results is the problem that we are seeking to address by moving to the improved module design reported in this paper. It is not yet possible to statistically verify that the new GL4 module exhibits lower variability than the existing standard module, though these early results are promising.

DISCUSSION

The available cooling power of the GL4 module depends on the volume of ^{4}He that is condensed during cycling, and on the fraction of the condensed ^{4}He that is subsequently consumed by parasitic loads while the module is running. We have developed a Mathcad model of the GL4 that allows us to model the condensation process and calculate the maximum theoretical cooling power as a function of module dimensions, fill pressure and condensation conditions. For a module of given size and fill pressure, the theoretical cooling power is governed by the temperature of the GL4 head during condensation, which is in turn determined by the temperature of the GM cold head. Hence a lower GM second stage temperature leads to higher condensation efficiency and better performance from the GL4. This is clearly illustrated by the graphical plot of calculated theoretical cooling power versus condensation temperature in Fig. 5. which shows that the lowest condensation temperatures are obtained with the RDK101/Zephyr, followed closely by the 2KGM/CNA11 and then the RDK101/CNA11. Cooling with liquid helium gives much poorer condensation efficiency.

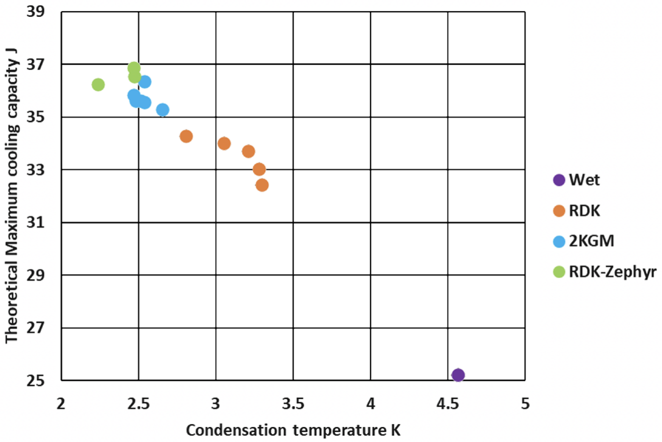

Figure 5. Calculated maximum theoretical cooling capacity of the GL4 module in relation to head condensation temperature.

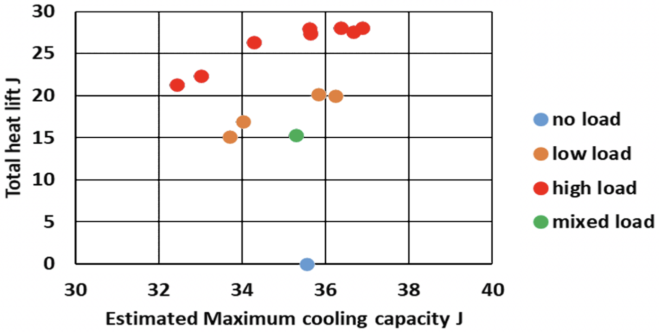

Figure 6. Illustrates the proportion of the theoretical cooling capacity that is actually available to the user of the GL4.

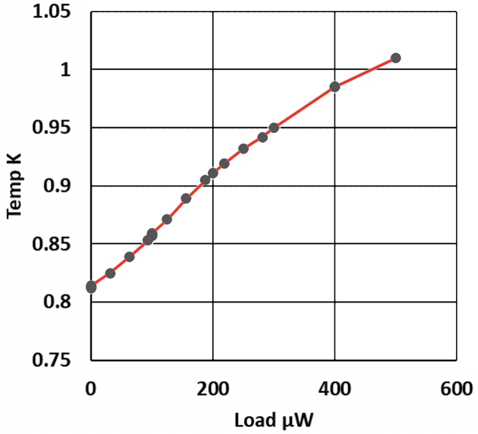

Figure 7. Load response of the GL4 module.

In practice the available cooling capacity is a lot lower than the theoretical maximum, as unavoidable parasitic loads always consume power. The fraction of the theoretical maximum cooling power that is available to the user of the GL4 depends on how the module is loaded.

At low applied loads parasitic losses are dominated by superfluid film creep, whereas at high applied loads losses are dominated by gas conduction. The effects of different loading patterns can be seen in Fig 6, which shows the total applied load (i.e. user-available heat lift) plotted against the estimated maximum theoretical cooling power. When running at low loads for a long time, approximately 50% of the total cooling capacity is consumed by parasitics, whereas when running at high loads for a shorter time this falls to <25%.

The temperature of the GL4 module increases with loading. The load response for a typical individual module of the new design, in Fig 7, is similar to that measured for our current standard GL4 modules [1]. At low loads the load response is almost linear, whereas at high loads it begins to flatten off. The GL4 module has two points where the user is able to sink heat loads; the film burner acts as a buffer stage and a significant fraction of the applied load, for example from the wiring to sensors mounted on the GL4 head, can be reduced by heat sinking to the film burner.

CONCLUSIONS

In this paper we present early results for a new design of GL4 <1 K module, tested with different GM cold head / compressor combinations. Our results clearly demonstrate that the temperature achieved by the GM affects the performance of the GL4 module. This is because the GL4 module performs better when its mainplate is at a lower temperature during condensation. A modest temperature difference of around 0.2 K in condensation temperature produces a significant difference in the cooling power of the GL4. When compared to the Sumitomo RDK101 cold head, Sumitomo's new 2KGM cold head produces significantly better performance from our GL4 modules, enabling longer run times and greater heat lift. Likewise, the RDK101 performs better when used with the Zephyr air-cooled compressor, which is more powerful than the CNA11 compressor. Other operational characteristics such as cooldown time and GL4 recycling time were the same for both RDK101 and 2KGM cold heads, when using the CNA11 compressor.

Whichever pre-cooling system is used, the performance of the new design of the GL4 module appears to be as good, or better than, the performance of the standard GL4 design. These early results indicate an average run time of around 45 hours when operated under a 100 µW applied load. As yet the dataset is not sufficiently large to verify that the new design is more consistent than the standard design in its performance from module to module. More data will be required to establish a difference in variability.

REFERENCE

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