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To cite this article: S T Chase *et al* 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **502** 012134

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Pre-cooling a $^3\text{He}/^4\text{He}$ dilutor module with a sealed closed-cycle continuous cooler

S T Chase¹, T L R Brien², S M Doyle² and L C Kenny¹

¹Chase Research Cryogenics, Cool Works, Unit 2 Neepsend Ind Est, Parkwood Road, Sheffield S3 8AG, United Kingdom;

²School of Physics and Astronomy, Cardiff University, Cardiff, CF24 3AA, United Kingdom

simon.chase@chasecryogenics.com

Abstract. A continuous closed cycle cooler to operate at a base temperature below 300 mK has been successfully designed and tested by Chase Research Cryogenics in collaboration with Cardiff University Astronomical Instrumentation Group. This compact, relatively low-cost unit has temperature and heat load capability of around 200 μW at 340 mK, and 400 μW at 450 mK. Here we discuss the suitability of this unit for precooling a miniature self-contained dilution module to produce a cryogen-free cooling platform capable of achieving a useful cooling power at temperatures of less than 100 mK.

1. Introduction

Ultra-low temperatures are required for a wide range of applications in photonics, quantum computing and astronomy [1]. However, refrigeration techniques for reaching 0.1 K and below are often large and expensive, with much greater cooling power than is needed for many of the next-generation sensor technologies now in development.

Miniature, self-contained dilution modules capable of providing just a few microWatts of cooling power, at operating temperatures between 50 and 100 mK, have been around for many years and several different designs have been described [2]. Typically, miniature dilutor modules are pre-cooled using single-shot, closed-cycle sorption coolers, which only remain at the temperatures required for operation of the dilution module for a limited duration. This limits the utility of the system since initial cooldown times can be rather long and cycling the single-shot pre-cooler will disrupt the dilution circulation. With adequate *continuous* precooling however, a miniature dilutor would be capable (in principle) of operating at ultra-low temperatures indefinitely.

The goal of this work is to develop a compact, closed-cycle dilution system for extended operation by integrating a sealed continuous pre-cooler with a miniature dilution module. We build on proof-of-concept work previously reported [3], in which a dilution module was pre-cooled using two ^3He sorption coolers working in tandem. The essential components of our system, the continuous pre-cooler and the miniature dilution module, have both been developed and improved since the initial proof-of-concept



stage and in this paper we discuss their integration into a continuous, self-contained, miniature dilution cooler.

2. Dilutor performance

The miniature dilution module is a sealed unit that contains a coolant mixture of ^3He and ^4He . Cooling is effected by circulating ^3He molecules across the phase boundary between a ^3He -rich phase and a ^3He -poor phase, as in a conventional dilution refrigerator. In the miniature module however, the coolant mixture is contained entirely within the module and no external mechanical pumps or gas handling systems are needed to drive the circulating flow. The flow is instead driven by the temperature difference between an evaporating still and a condensing point (condenser) cooled by the pre-cooler, and by osmotic pressure across the phase boundary in the mixing chamber. From the condenser the ^3He flows, as liquid, into the ^3He -rich phase in the mixing chamber. From there it passes through the phase boundary and is returned via a heat exchanger back to the still, where it is heated to evaporation and flows as gas back to the condenser. The quantity of ^3He required to charge the dilution module is only around 2 STP litres, which is an important consideration given the very high cost of ^3He . As the dilution module is sealed, no gas is consumed during its operation and it never needs to be re-charged. Nor does it contain any moving parts that could be a source of unwanted vibration for sensors mounted on the cold head.

We have investigated the performance of the dilution module to measure its cooling power and to assess its performance under various operational conditions, including under load and with different coolant compositions and volumes. During initial testing the dilution module's condenser was cooled using a Chase Research Cryogenics (CRC) 'Helium 7' single-shot pre-cooler capable of reaching temperatures below 300 mK, itself pre-cooled to 4 K using a Cryomech Pulse Tube system. The initial cooldown of the dilution module, shown in Figure 1, takes around 4 hours to cool from 400 mK to less than 100 mK. (Note, colour figures are available in the online publication).

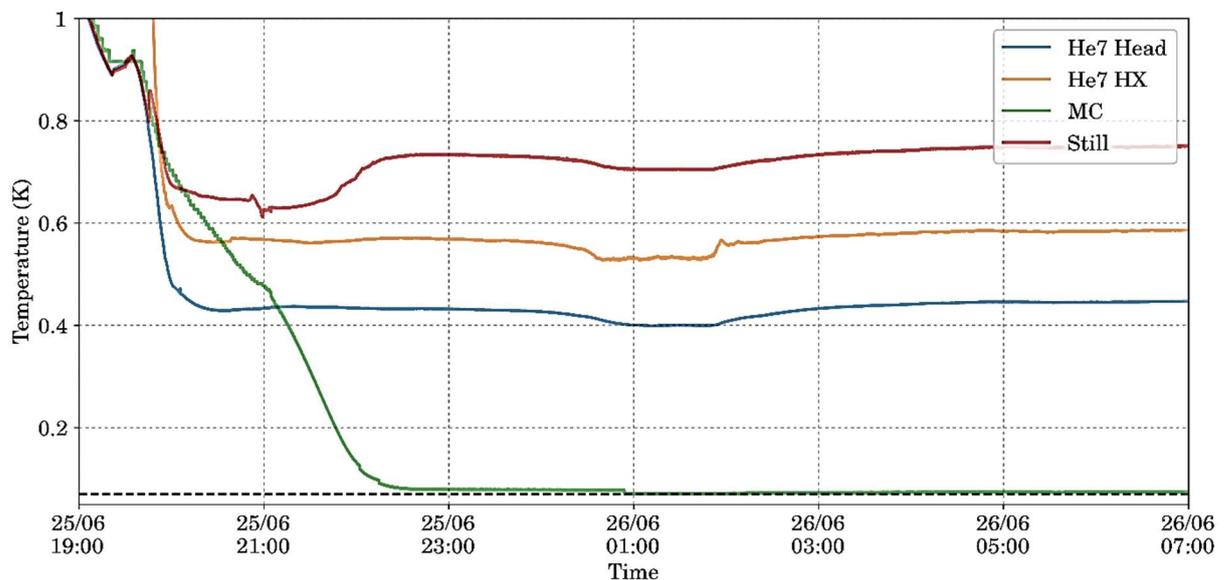


Figure 1. Cooldown of the dilutor module mixing chamber (MC)

The response of the mixing chamber or head temperature to applied loads was measured with the dilution module vertical, and with it tilted between 0 and ± 8 degrees to vertical, which affects the liquid ^3He flow through the system. The results are shown in Figure 2. The reasons for the slightly improved performance when tilted are not yet fully understood and point to some potential to further optimize the design of the module. The temperature of the head or mixing chamber strongly depends on applied load.

Results indicate that the dilutor module should have an operating temperature below 90 mK when the load on the dilutor head is around 3 μ W or less.

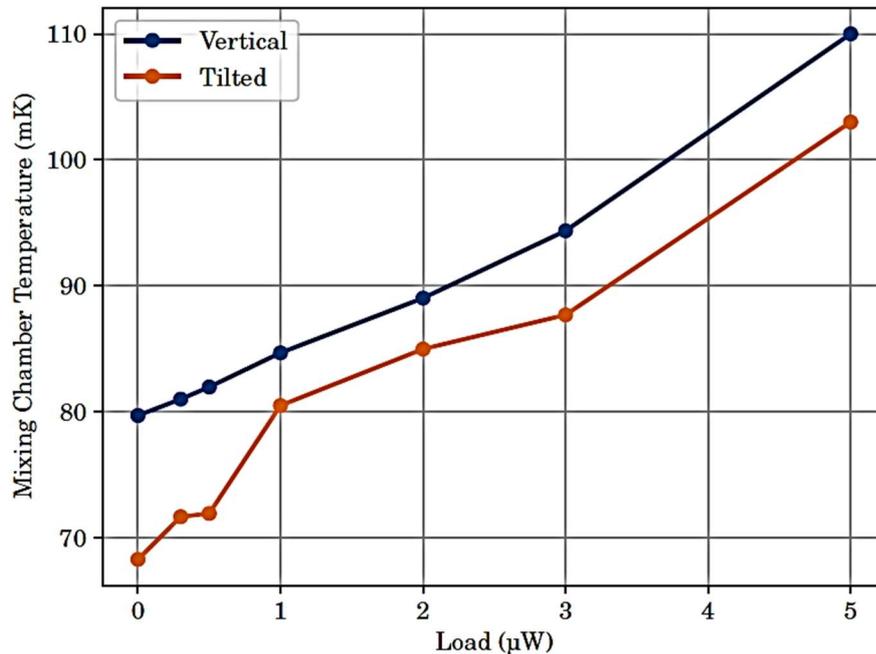


Figure 2: Dilutor mixing chamber temperature – load response

The dilution module was also tested with different coolant mixtures and volumes. In Figure 3, the temperatures of the still, condenser and mixing chamber or head are shown as a function of still power and coolant composition. The different mixture compositions are given in Table 1.

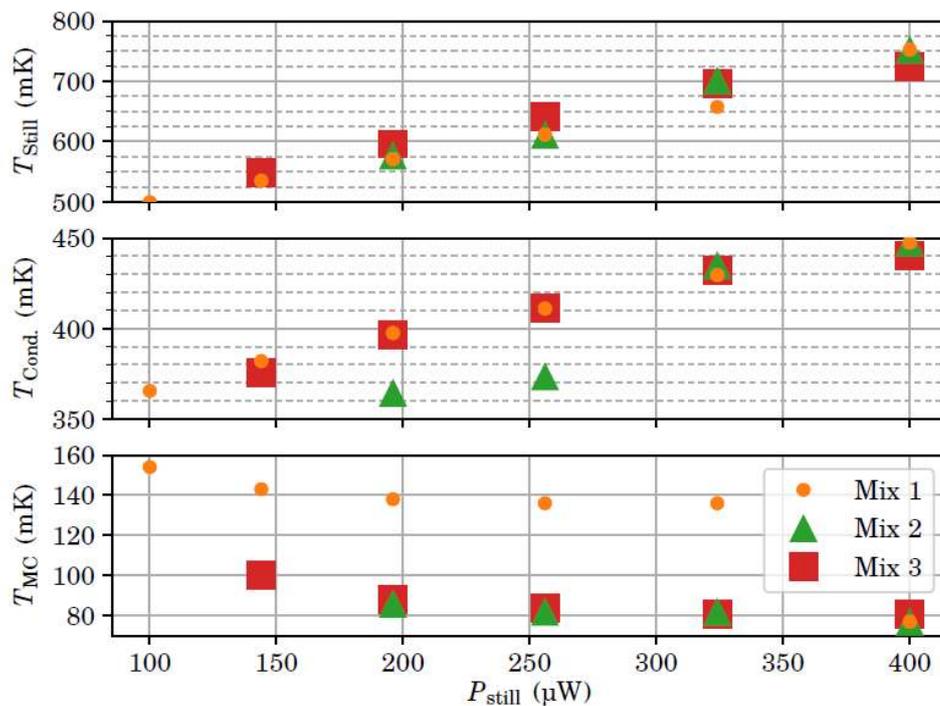


Figure 3: Temperature as a function of still power for different mixture compositions

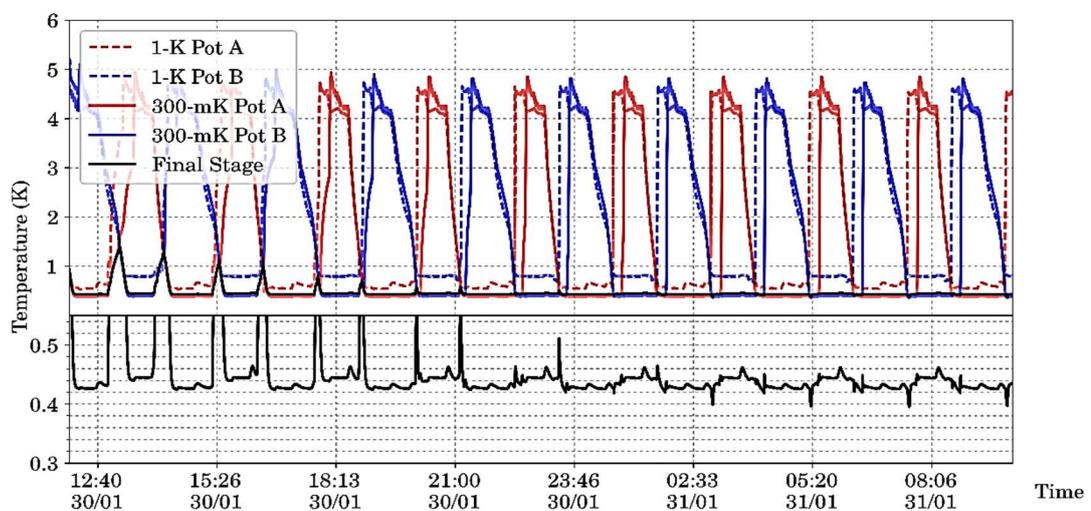
Table 1: Coolant mixture compositions tested

Mixture	Helium 3 STP litres (% of total volume)	Helium 4 STP litres	Total coolant volume STP litres
Mix 1	1.84 (46%)	2.14	3.98
Mix 2	1.92 (46%)	2.22	4.19
Mix 3	1.97 (47%)	2.27	4.24

3. Continuous cryocooler performance

The continuous sorption cryocooler operates essentially as two separate sorption modules cycled in antiphase. Both modules cool the same final evaporator, which will be thermally coupled to the dilution module condenser. Each sorption module consists of a ^3He and a ^4He pump, i.e. similar to a CRC single-shot ‘Helium 7’ cooler. An early prototype of this continuous cryocooler was described by Klemencic et al. [4], who demonstrated that it operated at an average temperature of around 300 mK under minimal thermal load. It remained stable at that temperature for a period in excess of three months before the system was switched off. The operating temperature at the final evaporator was subject to periodic fluctuations of a few tens of mK owing to the regular recycling of the system, however it could be stabilized using feedback control, at the expense of a rise in operating temperature. For example, with feedback control the early prototype supported an applied load of 20 μW at a stable operating temperature of 365.0 ± 0.1 mK for more than 24 hours [4].

A second improved prototype of this continuous cryocooler has been built for use as a pre-cooler for a 100 mK continuous cooling system developed for MUSCAT on the Large Millimeter Telescope [5]. Testing of the improved prototype has not yet been completed, however results with the first prototype demonstrated that the recycling parameters can be successfully tuned to give acceptable operation even under the high thermal loads expected in MUSCAT. These loads are estimated to be just under 400 μW (which is dominated by the load from the still, see Figure 3); at this loading the operating temperature of the first prototype (with optimized recycling) was 450 mK [5], which is adequate for pre-cooling the condenser of the miniature dilutor module. Figure 4 shows the temperature-time trace of the first prototype continuous cryocooler under a 400 μW load. The red and blue traces (online figure only) are the two sorption modules and the black trace is the final evaporator. The figure shows that the system takes some time to achieve a steady state, with the evaporator temperature averaging around 450 mK when no feedback loop is implemented to stabilise the temperature. The performance of the second prototype is expected to be better than the example shown here.

**Figure 4:** Temperature-time trace for the continuous cooler under a 400 μW load

4. Discussion

The efficiency of the miniature dilutor is largely determined by the operating temperature of the pre-cooler under the load imposed by the still [6]. A lower base temperature and flatter load characteristic would increase the circulation of ^3He and produce lower temperatures and more cooling power in the mixing chamber. Design changes made to the second prototype continuous sorption cryocooler should improve its performance as a dilutor pre-cooler. However, as demonstrated for MUSCAT, careful attention to minimizing the loading on the dilutor is likely to be the overriding factor determining the overall performance of the combined pre-cooler / dilutor system in practice.

When compared to conventional dilution coolers, the miniature dilutor described here has a very low cooling power, less than 1% for example of the cooling power at 100 mK of the system described by Uhlig [7]. Cost and size considerations aside, cooling power of that magnitude is not always needed for single photon or particle sensing applications. Many of the current and next-generation sensors for which applications are in development have very low power dissipation requirements, and a cooling power of only 1 μW is often sufficient for detector arrays of usable size.

Alternative compact, closed-cycle continuous cooler designs have been proposed, for example Bartlett et al. [8] describe a schema for a milli-Kelvin continuous cooler that utilizes two adiabatic demagnetization refrigerators (ADRs) working in tandem, connected to a common cold stage using magnetoresistive (superconduction transition) heat switches. The estimated cooling power of this system at a temperature of 300 mK is between 30 and 60 μW , rising to an estimated maximum of 150 μW at a temperature of 450 mK. That cooling power would be insufficient for precooling the miniature dilutor module we have developed.

A completely different design for a ‘compact’ continuous dilution cooler, that utilizes a ^4He pre-cooler operating at a temperature of around 1K, is described by Matthews et al. [9]. The dilution stage is intended to provide a cooling power of several tens of microWatts at 100mK, However the design involves two separate gas-handling systems and pumps that are external to the main cryostat, so though the dilution module itself is very compact, the gas handling system needed to support both the dilution module and the ^4He pre-cooler is not.

5. Conclusion

Our miniature dilutor module requires a pre-cooler capable of supporting a still power loading in excess of 300 μW , while cooling the condenser to a temperature that is below 450 mK. We can accomplish this using a continuous cooler that cycles two sorption coolers in antiphase through a common final evaporator. The size of the continuous cooler is approximately $200 \times 200 \times 240$ mm, and the weight is approximately 3 kg.

Our modelling and test results suggest that when these two sub-systems are integrated, the resulting continuous miniature dilution cooler will achieve more than 5 μW of cooling power at 100mK, whilst also offering rapid cool down and “push button” operation. These features more than meet the stated requirements for testing the next generation of detector wafers for astronomy and other applications.

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