Dilution Refrigerator with Direct Pulse Tube Precooling

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ABSTRACT

For experiments at sub-Kelvin temperatures, researchers usually work with Helium-3,4 dilution refrigerators (DR). DRs where a pulse tube refrigerator (PTR) precools the cryostat, are especially convenient to operate and more economical than traditional ones with liquid helium precooling. These so-called dry DRs consist of a two-stage pulse tube cryocooler, a Helium-3,4 dilution unit and an intermediate Joule-Thomson cooling stage.

In our new design, the circulating Helium-3 of the DR was precooled by the PTR in three heat exchangers to a temperature of about 2.5 K, and then directly run to the flow restriction of the dilution unit without further precooling. These three heat exchangers were attached at the first stage, at the second regenerator, and at the second stage of the PTR. An important feature of the PTR was utilized, namely the excess refrigeration capacity of its second stage regenerator, which can be used without impairing the cooling capacity and the base temperature of the second stage. The precooling temperature of 2.5 K was low enough to operate a DR.

Temperature sensors were placed in all critical locations of the cryostat. We give details of the temperature profile of the cryostat, and present cooling capacity data of the DR. The new condensation system allows for a very short and compact layout of the dilution cryostat.

INTRODUCTION

Helium-3,4 dilution cryostats are the workhorses for experimentalists doing research at milli-Kelvin temperatures. There are applications in materials research, nuclear research, quantum materials research, quantum information technology, metrology, astronomy or scanning tunneling microscopy (STM), to name just a few areas where milli-Kelvin temperatures are required. Over the past years, DRs with pulse tube precooling have become very popular with scientists.[1,2] No cryogens are needed for their operation, and thus this new type of DR is very convenient to operate; with prices of liquid helium steadily increasing, dry DRs are also more economical than conventional cryostats. A wide variety of dry DRs has become commercially available, from small “top-loaders”[3] to a DR with a refrigeration capacity of the mixing chamber of 1.5 mW at a temperature of 120 mK (CUORE experiment[4]).

In our paper, a DR is described where the condensation system of the circulating Helium-3 and herewith the entire construction of the cryostat has been simplified compared to standard dry DRs. There, the DR consists of three different cooling stages, namely the PTR, an intermediate Joule-Thomson stage and the dilution unit (DU). In our new design, the precooling of the

Cryocoolers 15, edited by S.D. Miller and R.G. Ross, Jr.

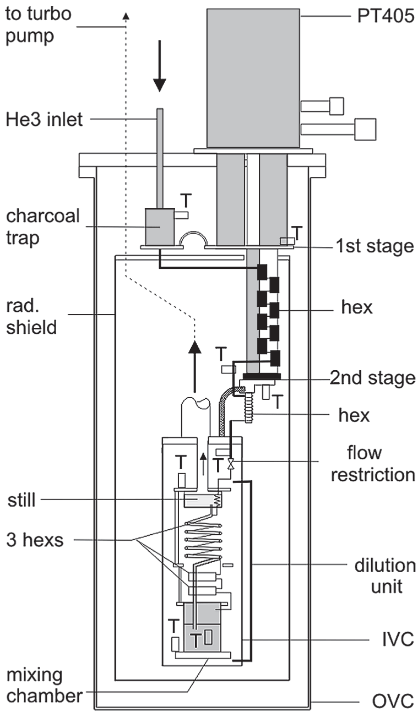

Figure 1. Cross-section of the DR. It consists of two main components, a PTR and a DU; they are situated in an outer vacuum can, a radiation shield and an inner vacuum can. Thermometers are labeled “T”. Total length of the cryostat (including the PTR) is just 1 m.

Helium-3 flow by the PTR was improved, and the heat exchanger of the JT-stage could be omitted entirely. Thus, in the re-designed concept, the dry DR consists only of two major components, the PTR and the DU. For the condensation of the Helium-3,4 mash at the beginning of an experiment, a compressor is no longer necessary, and the condensation pressure never exceeds 1.2 bar during running. The new refrigerator is shorter and easier to build than the dry DRs made previously.

CONSTRUCTION, OPERATION

A cross-section of the dry DR is shown in Figure 1. The cryostat is cooled by a standard commercial PTR (CRYOMECH, model PT405[5]). The Helium-3 gas enters the DR at a pressure of ≤ 1 bar via a charcoal trap which is mounted at the 1st stage of the PTR. In the trap, the gas flow is purified and precooled to a temperature of ~50 K; this is the only cold purifier in the DR system. Next, the Helium-3 is cooled in a heat exchanger which is mounted to the 2nd regenerator of the PTR. We know from theoretical and experimental work[6,7,8] that extra cooling capacity is available at this regenerator, in addition to the one at the cold ends of the PTR. There are different ways of designing this heat exchanger. Ours is made of eight small pipe sections that are clamped equally spaced to the regenerator tube (Figure 1). The Helium-3 input line is soft-soldered to the pipe sections, and thus a continuous heat exchanger is the result. The advantage of our concept is that the heat exchanger can easily be installed in a fully assembled DR[9]. Finally, the Helium-3 flow is liquefied and cooled to ~2.5 K in a heat exchanger that is mounted at the 2nd stage of the PTR. From there, it is directly run to the DU via a flow restriction without further precooling. The flow restriction is custom-made; it consists of a short piece of CuNi tubing with a wire inside and small Indium-sealed flanges for easy installation. An example of the cooldown of the Helium-3 flow can be found in an enthalpy diagram in Reference 10.

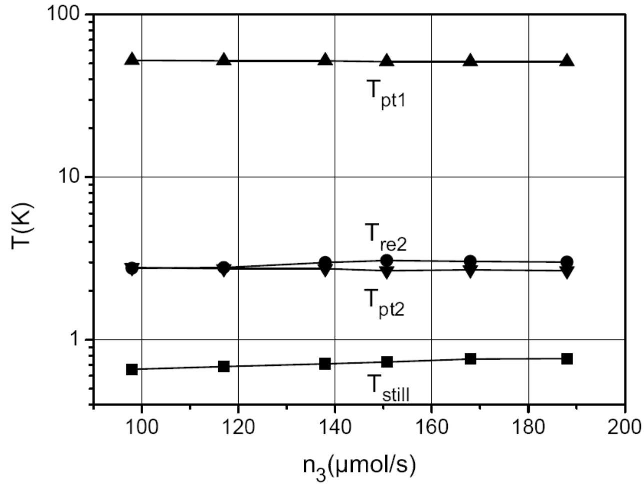

Figure 2. Temperatures of the dry DR as a function of the Helium-3 throughput. T_{pt1}: temperature of the 1st stage of the PTR; T_{re2}: temperature of the Helium-3 flow at the exit of the heat exchanger of the 2nd regenerator; T_{pt2}: 2nd stage of the PTR; T_{still}: temperature of the still.

The dilution refrigeration unit is a standard commercial unit made by Oxford Instruments.[11] It consists of a still, a continuous heat exchanger, two step heat exchangers and a mixing chamber; the step exchangers and the mixing chamber are equipped with silver sponges to overcome the thermal resistance barrier between the liquid Helium-3,4 and the casings of the mixing chamber and the heat exchangers, respectively. To circulate the Helium-3 in the DR, a turbo pump (Pfeiffer TMH 1601) was available.

Thermometers were attached in all critical positions of the DR (Figure 1). PT100s were used for the higher temperatures, Cernox resistors[12] for intermediate temperatures, and RuO chip resistors for temperatures below 1 K.

RESULTS

In Figure 2, four sets of temperatures are shown as a function of the Helium-3 flow rate. T_{pt1}, the temperature of the first stage, is not affected by the Helium-3 flow. T_{re2}, the temperature of the Helium-3 gas after it leaves the heat exchanger at the 2nd regenerator, is close to T_{pt2}, the temperature of the 2nd stage. This means that the enthalpy of the Helium-3 flow is almost entirely absorbed by the two heat exchangers of the first stage and of the 2nd regenerator. Thus, the heat load to the cold end of the 2nd stage is negligible, and T_{pt2} is always close to its base temperature, independent of the Helium-3 flow rate. Figure 2 indicates that the PTR could easily cool higher throughputs than the ones used in our work. Lastly, the still temperature is plotted in Figure 2. In order to achieve higher flow rates in the DR, heat has to be supplied to the still. At our highest circulation rates, the temperature of the liquid in the still reaches 0.75 K.

Figure 3 shows the temperature of the mixing chamber in dependence of the Helium-3 circulation rate with no electrical heat supplied. Base temperatures of the mixing chamber were at 8 mK, almost independent of the Helium-3 flow. The base temperatures measured were about what one would expect for the kind of DU utilized in our work.

In Figure 4, the refrigeration capacity of the mixing chamber is given; at a flow rate of 200 μmol/s and a temperature of 100 mK it has a value of 80 μW. Temperatures were measured inside of the mixing chamber in the liquid and outside at its bottom plate. Temperature gradients are small (~ 5 mK). This indicates that the silver sponge of the mixing chamber, which provides the thermal contact between the liquid and the bottom plate, is dimensioned adequately.

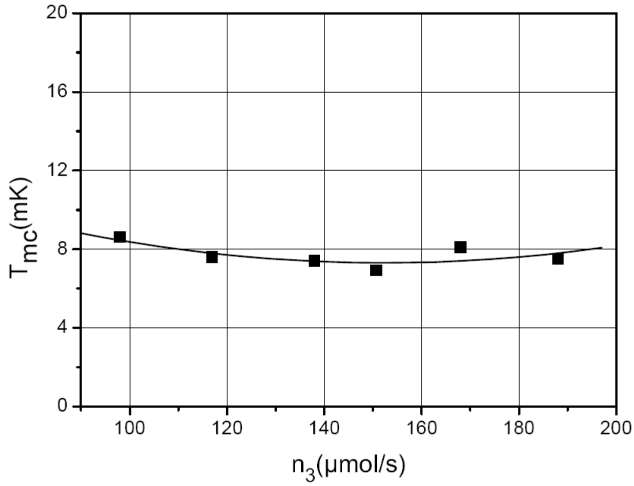

Figure 3. Base temperature of the DR as a function of the Helium-3 flow rate. The lowest temperatures reached in our apparatus were near 8 mK.

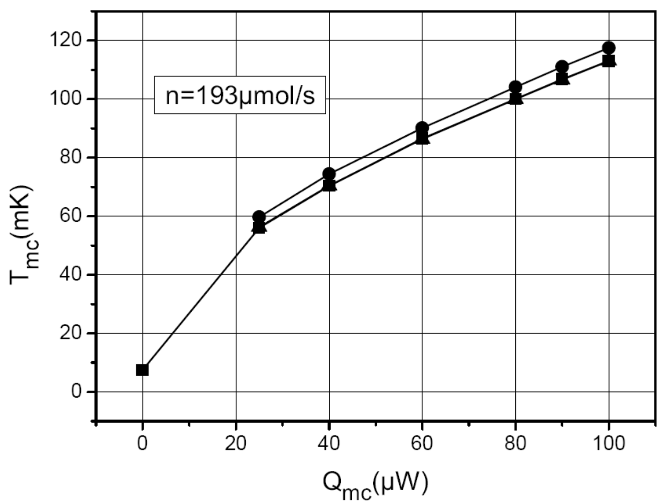

Figure 4. Mixing chamber temperature and refrigeration capacity of the DR at a high Helium-3 flow rate of 200 µmol/s. The lower curve is of a thermometer in the liquid, the upper curve of a thermometer attached to the mixing chamber bottom plate.

SUMMARY

Dilution refrigeration made simple! We have described a dry DR with a clearly laid out construction; the DR consists of a commercial PTR and a commercial dilution refrigeration unit. A gas purifier is integrated in the refrigerator. The intermediate cooling stage commonly used in dry DRs was made redundant by efficiently precooling the Helium-3 flow with the PTR. The characteristics of the cooldown and details of the cooling power of the DR are presented. Higher Helium-3 circulation rates and herewith cooling capacities of the mixing chamber of the DR are feasible with the concept introduced here.

ACKNOWLEDGMENTS

The author thanks F. v. Feilitzsch of the Technical University of Munich for making available his Oxford dilution refrigeration unit for this work, and J. Hoehne of VeriCold Inc. for support.

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