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On a ^{3}He Refrigerator Based on Closed-Cycle Cryocooler Cooling

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Abstract—At the Frank Laboratory of Neutron Physics, Joint Institute for Nuclear Research, work is underway to create gas-filled neutron detectors. To prepare the working mixture of gases, it is necessary to use pure ^{3}He, which is obtained by freezing impurities. A ^{3}He refrigerator is created for this purpose. The refrigerator can also be used to obtain low temperatures in a physics experiment. In this work, the operating modes of the refrigerator are studied. In the continuous mode of ^{3}He circulation, a temperature of 0.78 K is obtained. When ^{3}He vapor is pumped out by an external pump in a single cooling mode, a temperature of 0.52 K is reached. We also study the relaxation modes in which, with pre-condensed ^{3}He, the volume of the container plays the role of a pump. A mode is presented in which the temperature of the evaporator relaxes from 1 to 1.5 K within 11 days.

Keywords: ultralow temperatures, helium-3, cryocoolers, activated carbon pump

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INTRODUCTION

At the Frank Laboratory of Neutron Physics, Joint Institute for Nuclear Research the area of gas-filled thermal neutron detectors is traditionally developed [1–3]. One of the components of the mixture of gases filling such detectors is ^{3}He. The detector assembly technology involves the addition of pure ^{3}He in a preprepared mixture of other gases. At the end of its service life, it is necessary to refill the detector with a mixture of gases. Due to the high price of ^{3}He, the use of a new volume of the high-purity commercial ^{3}He for these purposes is very expensive. It seems more rational to extract ^{3}He from the mixture previously used in the detector by freezing it out. To do this, the mixture of gases must be cooled to temperatures below 3.3 K, corresponding to the liquid state of ^{3}He. These temperatures can be obtained in helium cryostats or using closed-cycle cryocoolers, for example, of the Gifford-McMahon (GM) type, and combining with them a refrigerator in which the liquefaction of ^{3}He occurs as well as pumping out its vapors.

This paper describes the design of a ^{3}He refrigerator intended for cleaning ^{3}He of impurities, with the cooling by a GM cryocooler. The operating modes of this refrigerator, which can be useful for conducting neutron experiments with low temperatures in the region of 1 K and below, are also considered.

DESCRIPTION OF THE EXPERIMENTAL SETUP

The design of the facility was largely determined by experience accumulated at Frank Laboratory of Neutron Physics, Joint Institute of Nuclear Research, in the use of cryocoolers [4–6]. Thus, in [4], a shaft cryostat with vertical loading was studied for placing samples with a diameter of up to 120 mm in the cold zone. In this design, the shaft was made from a thin-walled stainless steel pipe with a diameter of 150 mm. The thermal contact of the sample with the second stage of the cold head of the cryocooler was facilitated using a heat exchange gas ^{4}He at a pressure of 1–10 mbar. At a cold-head power of 0.7 W (temperature 4.2 K), which was used in the cryostat, the final temperature reached 5 K. It was limited by the design features of the cryostat, and the effect of the heat-exchange gas on it was not noted. Subsequently, measurements of the heat gain along the shaft were carried out in the pressure range of 1–20 mbar using the heat-exchange gas ^{4}He [5]. The value of this heat influx turned out to be insignificant and barely affected the final temperature.

Based on these measurements, it was decided to place the regenerative part of the cold head inside a vertical shaft similar in size to that in [4]. When filling the shaft with gaseous helium at a pressure of up to 20 mbar, it was to be expected that the cryocooler would operate without a significant loss in cooling capacity.

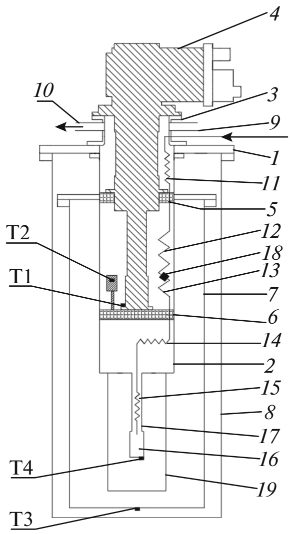

Fig. 1. Scheme of the cryostat with a ^{3}He refrigerator: *1*, main flange; *2*, container; *3*, cryostat collector; *4*, cold head; *5* and *6*, heat exchangers; *7*, heat shield; *8*, vacuum case of the cryostat; *9*, pipe; *10*, nozzle; *11–14*, sections of the heat exchanger; *15*, choke; *16*, evaporator; *17*, thin-walled tube; *18*, activated-carbon pump; *19*, heat shield; T1, T2, T3 are silicon diodes; T4 is the thermistor.

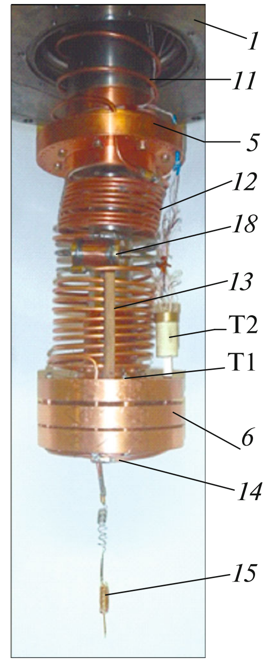

Fig. 2. Refrigerator heat-exchanger system. Designations as in Fig. 1.

In this work, the cryostat was equipped with a GM cryocooler with a capacity of 1.5 W at 4.2 K. A ^{3}He refrigerator was placed on the cold head of the cryocooler . The cold head and refrigerator units were oriented vertically from top to bottom. The design of the cryostat is shown in Fig. 1. The ^{3}He refrigerator represent a column of heat exchangers located on the regenerative part of the cold head. Container *2*, a pipe with a diameter of 150 mm made of thin-walled stainless steel and a length of 390 mm, was mounted below main flange *1*. A cold head *4* was installed on the cryostat manifold *3* coaxial with the container *2*. The length of the container was determined based on the requirement to accommodate the cold head and heat exchangers in it. Heat exchangers are installed on the first and second stages *5* and *6* respectively, which provide a thermal coupling between the container wall, the cryocooler stages, and helium. Heat transfer between the outer surface of the heat exchanger and the inner wall of the container is carried out due to the thermal conductivity of helium in a thin gap. Heat shield *7* is mechanically connected to the container wall at the level of the first stage of the cryocooler; *8* is the vacuum case of the cryostat. ^{3}He is fed into the container through the pipe *9* and is pumped out through nozzle *10*. Tube *9* passes into a tube heat exchanger, consisting of several series-connected sections *11–14*. Heat exchanger *14* ends with a choke *15* providing the necessary ^{3}He condensation pressure. Liquid ^{3}He accumulates in the evaporator *16*, which is connected to the container through a thin-walled tube *17* made of stainless steel with a diameter of 12 mm and a length of 60 mm. An activated-carbon pump is installed between the heat-exchanger sections *18*, which absorbs impurities in ^{3}He. Helium ^{3}He vapor from the evaporator enters the container and is then pumped out through a nozzle *10*. An important element of the refrigerator is heat shield *19*, which assumes a temperature close to that of the second-stage cold head and minimizes heat gain to the evaporator.

The temperature was measured by sensors: silicon diodes T1, T2, and T3, and thermistor T4. Temperature sensor T1 is located on the second stage of the cold head; T2 sensor is located 4 cm above heat exchanger *6*, sensor T3 is located at the bottom of the heat shield *7*, sensor T4 is installed outside the ^{3}He evaporator. Sensor T2 was inside a vessel made of heat-insulating material. The thermal coupling of this sensor with helium was carried out through a copper heat pipe, which was removed from the flask and had a heat-exchange surface with helium of about 2 mm^2. It was assumed that when working with ^{4}He according to its indicators, it is possible to record the appearance of the level of liquid helium.

Figure 2 shows a photo of the heat-exchanger system, and Fig. 3 presents a photo of the low-temperature part of the refrigerator. In Figs. 2 and 3 the numbering of the elements coincides with the numbering in Fig. 1.

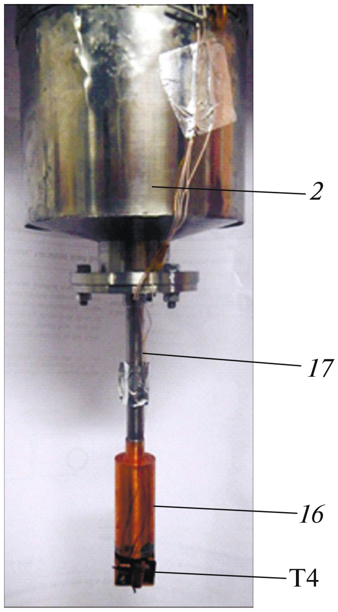

Fig. 3. Low temperature part of the refrigerator. Designations as in Fig. 1.

RESULTS

Experiments with ^{4}He

To test the performance of a cryocooler enclosed in a container, experiments were initially carried out using ^{4}He. 100 liters of ^{4}He were liquefied, in this case, cooling to 2.3 K occurred without the use of pumping. This temperature corresponds to the certified final temperature of the cryocooler, if it were operated in a vacuum cryostat. To keep the second-stage temperature at 4.2 K, a power of 1.6 W was required, which is slightly more than the expected certified power of 1.5 W.

Experiments with ^{3}He

After turning on the cryocooler, ^{3}He in an amount of about 20 L entered the refrigerator container through nozzle *10* (Fig. 1). Further cooling was carried out in two phases. At the first phase lasting 25 h, the circulation of ^{3}He through heat exchangers was not carried out. At the second phase, a hermetic spiral vacuum pump with a capacity of 35 m^3/h. ^{3}He was pumped out through nozzle *10* and returned back through tube *9* into the heat-exchanger system and the choke, after which it went to the evaporator. In total, it took 36 h to cool the evaporator to a temperature of 2.3 K. The cooling process is shown in Fig. 4.

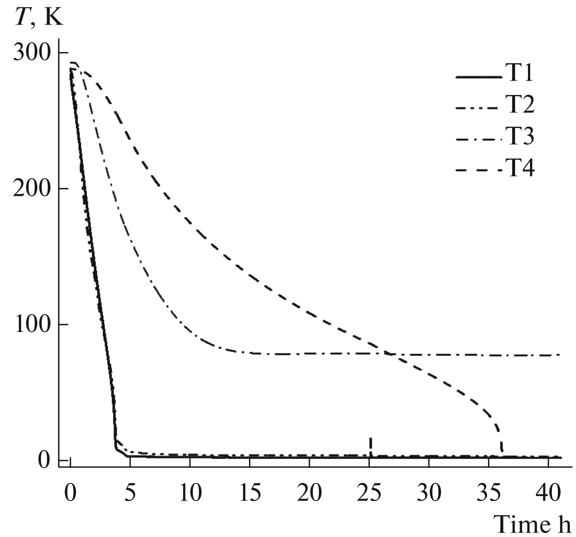

Fig. 4. Refrigerator cooling process: graphs of temperature changes of sensors T1–T4 over time.

Upon reaching this temperature, the liquefaction of ^{3}He occurred, and the temperature of the evaporator became less than 1 K. As a result, the temperature of the evaporator reached 0.78 K and could be maintained for an arbitrarily long time at constant ^{3}He condensation. This is how continuous operation of the refrigerator is carried out (Fig. 5). The temperature 0.78 K is determined by the conductivity of nozzle *10* (Fig. 1), which has a diameter of 16 mm and a length of 100 mm, as well as the pumping speed of the pump used.

In the single mode of operation of the refrigerator, in which ^{3}He is not supplied to the heat-exchanger system, the evaporator temperature drops to 0.52 K. Figure 6 shows the time dependence of the evaporator temperature during the transition from the continuous to single mode and vice versa. The transition was carried out by opening–closing the supply valve ^{3}He in the heat exchangers. In this case, the evaporator temperature varied from 0.78 to 0.52 K.

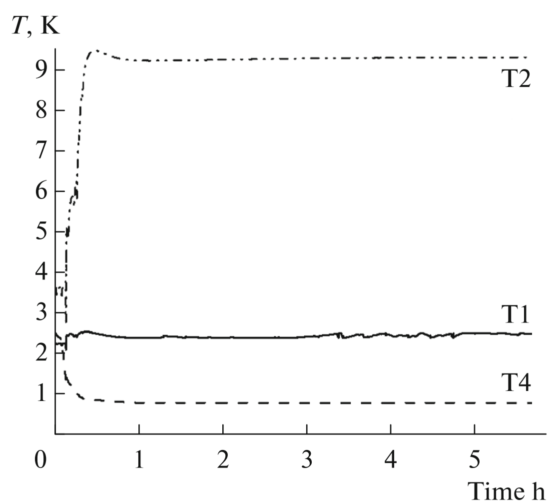

Fig. 5. Continuous operation of the refrigerator: graphs of temperature changes of sensors T1, T2, and T4 over time.

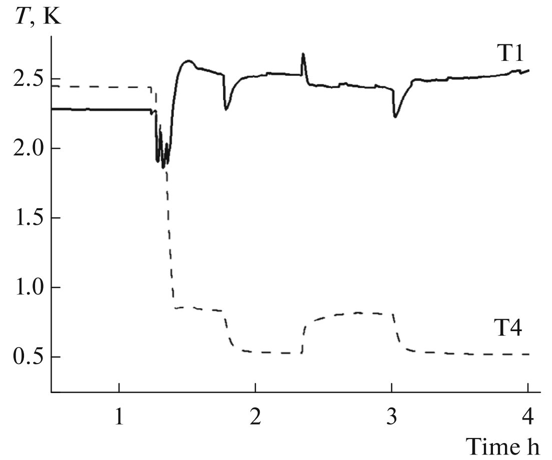

Fig. 6. Transition from the continuous to single mode and vice versa: graphs of temperature changes of sensors T1 and T4 over time.

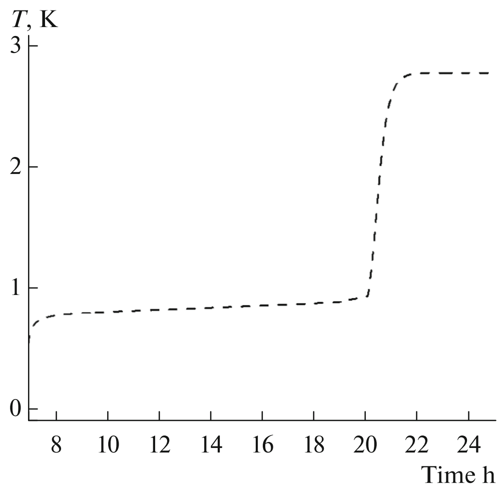

Fig. 7. Relaxation mode: a graph of temperature change of the T4 sensor over time. The temperature of the evaporator slowly increases from 0.85 to 1 K in the interval from 8 to 20 h.

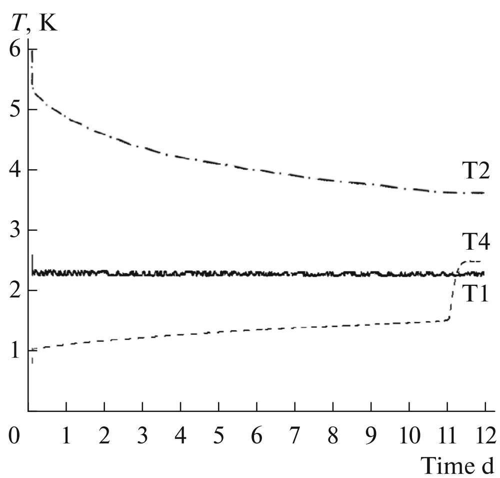

Fig. 8. Relaxation mode: graphs of temperature changes of sensors T1, T2, and T4 over time. The evaporator temperature slowly increases from 1.05 to 1.5 K over 11 days.

Relaxation Modes

In the next stage, the operating modes of the refrigerator with zero external pumping speed of ^{3}He with an evaporator preliminarily filled with liquid ^{3}He were studied. These modes can be called relaxation modes. We note that the cryocooler does not stop in these modes.

The time dependence of the evaporator temperature after turning off the spiral pump of ^{3}He was studied. In this case ^{3}He did not evaporate into the container that acted as a pump. If, after the implementation of the single mode and upon reaching 0.52 K, the external pumping was turned off, the evaporator temperature reached 0.85 K fairly quickly and then slowly increased to 1 K (Fig. 7). Further, the evaporator was completely dried, and its temperature rapidly increased to 2.7 K and stabilized. Similarly, if the continuous mode was terminated at 0.78 K and external pumping and condensation were stopped, then the evaporator temperature reached 1.05 K quite quickly and then increased to a temperature of 1.53 K in 11 days until the evaporator dried (Fig. 8). Then, as in the first case, there was a sharp jump in temperature to 2.5 K.

CONCLUSIONS

Currently, the presented cryostat is used for the cryogenic cleaning of ^{3}He from impurities. The process of cleaning and filling the detector is carried out in several stages. The gas mixture is pumped from the detector into a low-pressure cylinder (less than 1 bar). The mixture is then pumped into another cylinder through activated carbon cooled with liquid nitrogen. The next stage of purification is provided by the cryostat presented in the work. However, a pressure of at least 7 bar is required to fill the detector. For this, the resulting clean ^{3}He is compressed by a sorption pump cooled to 3.8 K by a closed-cycle cryocooler located in another cryostat. The sorption pump is a chamber with a volume of 200 cm^3 with high-strength walls, 25% of which are filled with activated carbon. At a temperature of 3.8 K, the pump absorbs 25 liters of ^{3}He, which after heating to room temperature creates a pressure of 125 bar. The amount of ^{3}He, obtained in this way, provides the filling of any detector operating at Frank Laboratory of Neutron Physics. It should be noted that sorption pumps with cryocooler cooling were developed by myself earlier and are presented, for example, in [7–9].

The cryostat can be used for physics research in the field of solid state physics. In this case, the sample is placed outside at the bottom of the evaporator. In the future, a similar design will be used as a source of liquid ^{4}He, and liquid or chilled ^{3}He, which inside the vacuum cryostat can power other devices, such as dilution refrigerators of ^{3}He in ^{4}He [10]. This design can be a heated system; in this case, in the relaxation mode, it can be used as a cooler for a scanning tunneling microscope at a temperature level of 1 K, along with a setup [11, 12] operating at a temperature of 4.2 K.

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