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High cooling capacity ^{3}He – ^{4}He dilution refrigerator*

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Contents

Abstract. **The paper is based on a report presented at the scientific session of the Physical Sciences Division of the Russian Academy of Sciences dedicated to the 90th anniversary of the founding of the P.L. Kapitza Institute for Physical Problems of the Russian Academy of Sciences (IPP RAS). The traditional area of applied research at the IPP RAS is the study and development of low-temperature equipment. In 2022, the United States and the EU imposed sanctions on high-tech exports to the Russian Federation, which included cryogenic equipment. This paper presents the results of testing a promising domestic high cooling capacity refrigerator based on endothermic dilution of the isotope ^{3}He in ^{4}He.**

Keywords: liquid helium, dilution refrigerators, helium-3

1. Introduction

The traditional area of applied research at the P.L. Kapitza Institute for Physical Problems of the Russian Academy of Sciences (IPP RAS) is the study and development of cryogenic equipment [1]. Institute researchers made a significant contribution to the science, technology, and defense capability of the USSR. For example, for the successful development and implementation of a new turbine method for producing industrial oxygen, Academician P.L. Kapitza, the founder of the institute, was awarded the title Hero of Socialist Labor, and the IPP RAS, headed by him, was awarded the Order of the Red Banner of Labor in 1945 [2]. In early 2022, the United States and the EU imposed sanctions on high-tech exports to the Russian Federation, which include cryogenic equipment. Moreover, in the summer of 2023, the IPP RAS was included in the Specially Designated Nationals (SDN) list of the US Department of the Treasury's Office of Foreign Assets Control (OFAC) [3]. In this regard, some types of low-temperature equipment have become inaccessible to Russian researchers and there was an urgent need to develop and produce domestic analogues.

Cryogenic refrigerators based on endothermic dissolution of the isotope ^{3}He in ^{4}He have become indispensable tools in scientific research at temperatures T significantly below 0.3 K, at which macroscopic quantum phenomena can often be observed. Earlier, researchers at the IPP RAS designed a small-size dissolution cryostat that ensures scientific experiments in the temperature range from 0.05 to 300 K [4]. This universal and compact device has a wide range of scientific research applications from solid-state physics [5] to astronomical observations [6]. However, a parameter of this cryogenic cryostat that significantly limits its practical application is its relatively small cooling capacity $\dot{Q}$ (< 1 μW).

At present, the main manufacturers of high cooling capacity cryostats for dissolution of ^{3}He in ^{4}He are Bluefors (Finland, www.bluefors.com) and Oxford Instruments (Great Britain, www.oxinst.com). Refrigerators from these foreign manufacturers operate in the range from ~ 0.1 K to ~ 5 mK, with $\dot{Q}$ of such refrigerators varying in the range from 0.1 to 1 mW at a dilution chamber temperature $T_{\rm mc} = 0.1$ K. Under conditions of large-scale sanctions from the collective West, in great demand in the Russian Federation are domestic refrigerators with a minimum dilution

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Figure 1. High cooling capacity ^3He–^4He dilution refrigerator.

chamber temperature $T_{mc} \sim 10$ mK, a relatively large experimental volume (the diameter of the flange for fastening samples is no less than 400 mm), and a high cooling capacity ($\dot{Q} \geqslant 400$ μW at 0.1 K). Recently, within the framework of the experimental design work of the Bauman Moscow State Technical University together with the Federal State Unitary Enterprise Dukhov Automatics Research Institute and Cryotrade Engineering LLC, Russian dry cryostats of high cooling capacity have been developed. Researchers at the IPP RAS have taken an active part in the design, development of technologies, and production of the dilution stage for the refrigerator (Fig. 1), which is intended to replace the products of foreign manufacturers. Some test results of this refrigerator are presented below.

2. Dilution refrigerator

London [7] put forward the idea of using endothermic dilution of the isotope ^3He in ^4He to obtain ultra-low temperatures, which was then developed in [8]. Das et al. [9] and Neganov et al. [10] were the first to implement this method in practice. Later, Edelman [11] demonstrated a continuously operating refrigerator, in which the temperature of the circulating ^3He isotope never rises above 1 K. Various designs of cryogenic dilution refrigerators are considered in more detail, for example, in the book by Lounasmaa [12]. The design of the dilution refrigerator was further significantly perfected by Uhlig, who developed a so-called 'dry cryostat' [13, 14]. Thus, the user has become completely relieved of the need to both monitor the presence and maintain the required level of cryogenic liquids in the external cooling circuit.

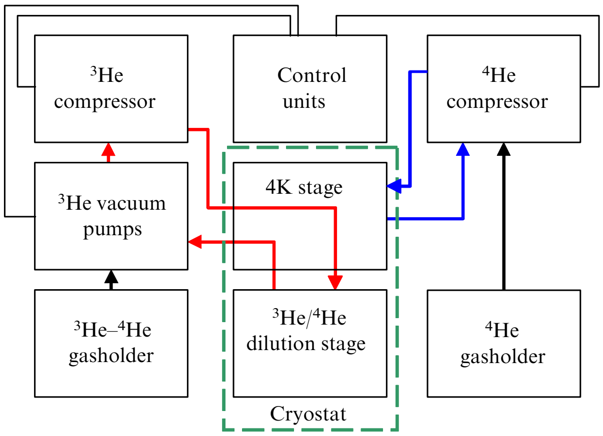

Figure 2. Block diagram of ^3He–^4He dilution refrigerator.

Figure 2 shows a block diagram of a dilution refrigerator. The refrigerator design has two circuits for gas circulation using compressors and oil-free vacuum pumps (spiral and turbomolecular). The latter, as well as the valves of the gasholders for ^4He and the $^3He-^4He$ gas mixture, are monitored by a control unit. The ^4He isotope circulation circuit, which is used in the operation of Gifford–McMahon [15] and Stirling [16] cryocoolers, is shown in blue (on the right). In the stationary regime, helium in this circuit partially condenses in the 4-K stage. Thus, the first circuit is used to pre-cool the helium isotope gas mixture circulating in the second closed circuit (on the left, red arrows) to $T \sim 4$ K. In the stationary regime of the dilution refrigerator operation ($T_{mc} \leqslant 0.1$ K), almost all of the ^4He isotope (Bose particles) condenses in the channels of the dilution stage into a superfluid state [17, 18] (Bose–Einstein condensate) and, in fact, only the gas of ^3He Fermi particles circulates in the second circuit.

Thus, the cooling capacity $\dot{Q}$ of the refrigerator is given by the circulation $\dot{n}$ of the ^3He isotope in the system in the form

$$\dot{Q} \approx 82 T_{mc}^2 \dot{n} - 5.2 \times 10^2 \frac{R_{Km}}{A} \dot{n}^2 - \dot{Q}_0 \,, \qquad (1)$$

where the first term describes absorption of heat during the dilution of ^3He in ^4He, and the second term describes the recovery of heat in the heat exchangers (R_{Km} is the average value of the Kapitza resistance of the surface through which heat exchange occurs, and A is the area of the heat exchange surface). The third term $\dot{Q}_0$ describes the unavoidable parasitic heat influx. Formally, expression (1) is derived for the case of a continuous heat exchanger with an optimal surface area distribution [19]; however, with some limitations, it is also true for the case of a set of step heat exchangers [20].

Red dots in Fig. 3 show the results of a design test (see Fig. 1) at $\dot{n} \approx 0.35$ mmol s^{-1}. For comparison, black squares show the data from [20], and the continuous curve is the calculation at $\dot{Q}_0 = 0.2$ μW according to (1).

In conclusion, we note the prospects for using the developed dilution refrigerator, for example, in supercon-

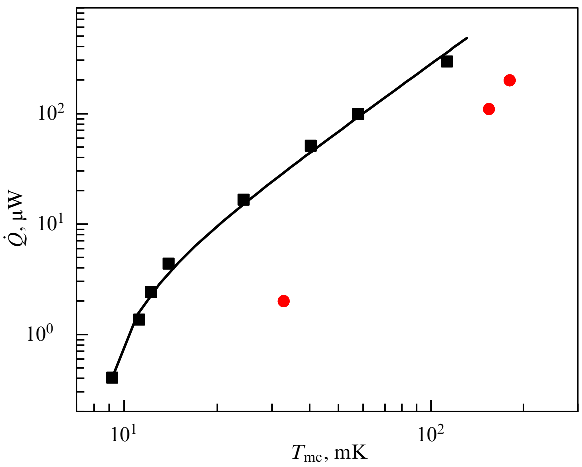

Figure 3. Dependence of cooling capacity $\dot{Q}$ on temperature $T_{\rm mc}$ of dilution chamber with constant ^{3}He circulation of $\dot{n} \approx 0.35$ mmol s^{-1}: black squares are data from [20], and red dots are results of testing prototype. Continuous curve is calculation according to (1).

ducting computing devices operating in the vicinity of absolute zero temperatures ($T \sim 10^{-2}$ K). Such low temperatures are needed to suppress thermal noise affecting the operation of Josephson qubits [21]. Moreover, to obtain significant computing power with such devices, it is necessary to use a significant number of qubits (> 100) simultaneously, which is associated with the presence of a large number of supply lines. For the latter reason, a particularly high cooling capacity is needed to neutralize the heat flow through the supply lines.

Another advantage of the dilution refrigerator is that a strong magnetic field has almost no effect on its characteristics. A significant cooling capacity of the developed cryostat allows massive experimental assemblies to be cooled, which can be used, for example, to obtain temperatures $T < 10^{-3}$ K by the method of nuclear adiabatic demagnetization [20, 22]. Recently, using this method to obtain ultra-low temperatures, new superfluid phases of liquid ^{3}He were discovered [23].

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