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Jet pump for liquid helium circulation through the fast cycling magnets of Nuclotron

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Abstract

Nuclotron is the first fast cycling superconducting synchrotron intended for the acceleration of high-energy nuclei and heavy ions. Its cryogenic system includes two helium refrigerators with a total capacity of 4000 W at 4.5 K. The 251.5 m long accelerator ring consists of 144 superconducting dipole and quadruple magnets. The magnets connected in parallel are refrigerated by a two-phase flow of boiling helium. In order to increase liquid helium flow directed to the superconducting magnets, jet pumps are used. We explain theoretical and experimental results that allow one to determinate main technical specifications and optimal geometric dimensions of the jet pumps. The experience of using this device and corresponding flow diagrams are described.

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Keywords: Nuclotron; pumps; helium

1. Introduction

The jet pump is an extremely simple, cheap device that does not require any additional systems for its operation. It consists of a nozzle, a cylindrical mixing chamber and a diffuser (Fig.1). In the course of its work a jet of compressed gas is accelerated in the nozzle and leads the injected stream. The speed of both streams are equalized in the mixing chamber.

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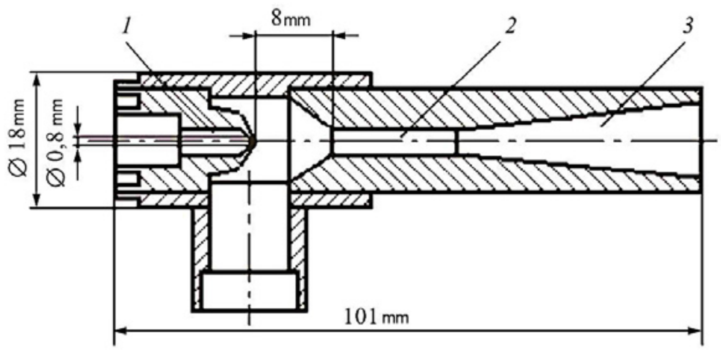

Fig. 1. Jet pump. 1 – nozzle; 2 - cylindrical mixing chamber; 3 – diffuser

The stream formed by mixing passes through the diffuser where its velocity is reduced and the pressure increases. An important advantage of the jet pump is that it can be constructed in a conventional workshop and quickly delivered to the customer. Furthermore, it is reliable at low temperatures.

2. History of the development

History of the development, implementation and improvement of jet pumps at JINR began in the 1970s and continues to this day. The first stage was the creation of a jet pump to achieve a temperature of 1.8 K by means of pressure decrease in the vessel of liquid helium (Fig. 2a). The next stage was using a jet pump to circulate a flow of single-phase helium at supercritical pressure for cooling superconducting devices. The scheme of that experiment is presented in Fig. 2b.

Stream G1 increases its velocity using the nozzle at the exit of the last heat exchanger of the refrigerator and then is carried away by the stream G2. The mixed stream G3 flows from the jet pump and, after cooling in the coil placed in the liquid helium, is fed to the cooled magnet. At the output of the magnet the stream is divided into two parts. One of them is directed to the jet pump, the other, equal to G1, to the reservoir. Unlike the system with a mechanical pump, in this case no power is added.

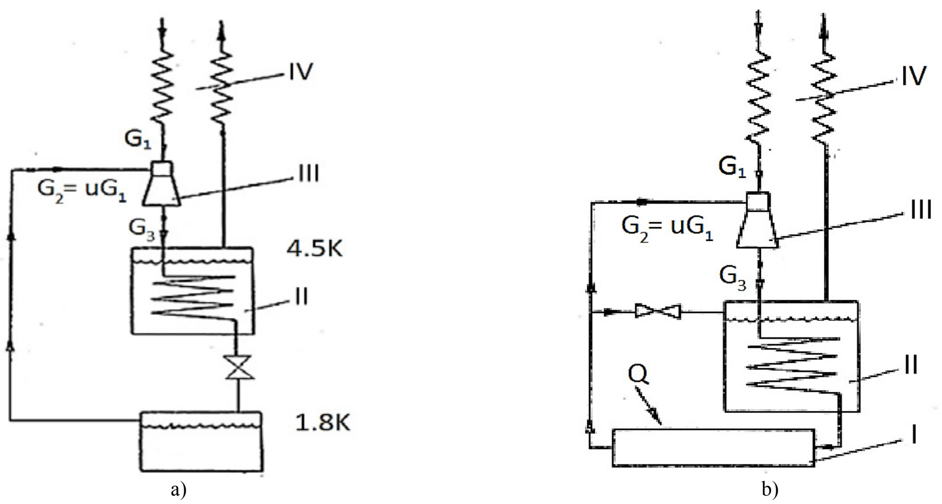

Fig. 2. A basic diagram of the circulating refrigeration system with a jet pump. I – cooled magnet, II – liquid helium reservoir, III – jet pump, IV – heat exchanger of the refrigerator

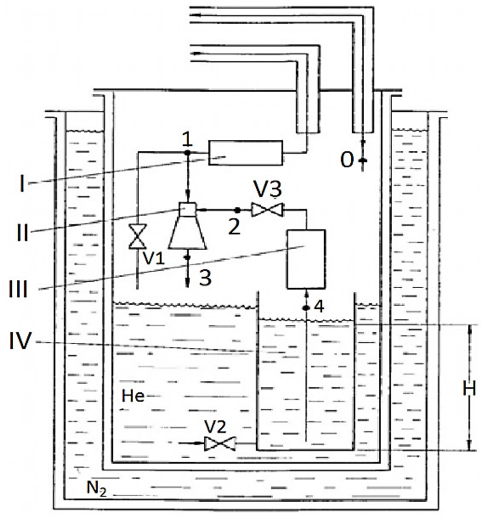

Fig. 3. Diagram of the experimental setup. I – filter-adsorber, II – jet pump, III – electric heater, IV – measuring vessel

This experiment revealed an advantages of such method of cooling compared to immersing the magnet into the bath of liquid helium or using mechanical pumps. However, even then it was clear that the two-phase helium cooling method holds great promise, of course, when the jet pumps are used. These perspectives were as follows: heat from the magnet is transferred to the helium without increasing its temperature, moreover, the temperature of the helium two-phase mixture at the outlet of the magnet is lower than the input due to the hydraulic resistance of the magnet. This cooling method has been tested with an experimental setup specially created for this purpose in 1980 (Fig.3).

The levels of liquid in the cryostat and in the measuring vessel are the same when valve V2 is open. In this case the mode is adjusted so that the level may remain constant. Upon closing valve V2, the level of liqud decreases in the the measuring vessel, and also increases in the cryostat.

The results showed that the jet pumps can be successfully applied to cool any devices using a biphasic helium. It was found that the expressions used for calculation of this process are valid only for those cases when the speed of the flow in the mixing chamber does not exceed the speed of sound.

3. Jet pumps as the part of cryogenic system of the Nuclotron

Development of superconducting devices, cryogenic systems and jet pumps continued in subsequent years at JINR. Nuclotron was created, which is the first superconducting fast-cycling synchrotron and is intended to accelerate nuclei and heavy ions. It was built in 1987-1992 at JINR Veksler and Baldin Laboratory of High Energy Physics. Nuclotron is 251.1 m length and consists of 96 dipole, 64 quadrupole magnets and 28 multipole correctors. The concept of its cryogenic system includes a large number of technical ideas and solutions never used before. Most significant of these were such as fast cycling superconducting magnets, refrigeratin by two-phase helium flow, very short time for cooldown to the operating temperature, parallel connections of all cooling channels, wet turboexpanders, screw compressors with a pressure rise of more than 25 in two stages. These technical solutions allowed the creation of not only efficient and reliable system, but also one which is unusually inexpensive.

Cryogenic system of the Nuclotron (Fig. 4) is based on using of two helium refrigerators with total capacity of 4000 W at 4.5 K. Cryogenic cycle of these refrigerators includes three turbo expander, a bath of liquid nitrogen, “wet” expansion turbine and also a wound-coil heat exchangers. The system provides purification of helium from the oil and all the other impurities. Operating pressure at the inlet of refrigerators is 2.5 MPa. Helium is compressed by means of two screw compressors and additional piston-type compressors. In order to increase the flow of helium passing through the magnets jet pumps are used. An important milestone in the history of the use of jet pumps was the inclusion of them in the cooling system of the Nuclotron in 2002 (Fig. 4). It made it possible to reduce the number of operating compressors and increase the energy efficiency of the whole system at least by 25%.

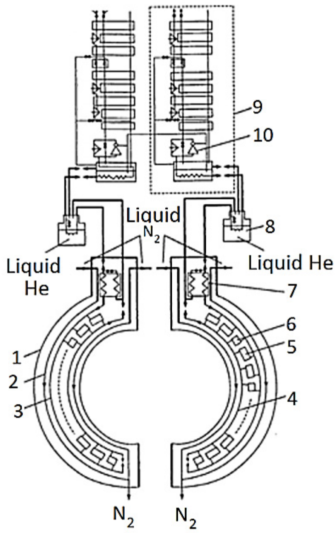

Fig. 4. Schematic diagram of a cryogenic helium system of the Nuclotron. 1- vacuum jacket; 2 - heat shield; 3 – supply header; 4 – return header; 5 – dipole magnet; 6 – quadrupole magnet; 7 – subcooler; 8 – separator; 9 – refrigeration unit; 10 – gas holder; 11 – receiver; 12, 14, 15 - piston-type compressor; 13 - drying unit; 16 - oil purification unit; 17 – screw compressor

In addition, increasing the helium flow passing through the magnets allowed us to overcome the difficulties associated with helium pumping through parallel channels of the magnets and provided a reliable and efficient operation of the Nuclotron.

At the moment, we have an extensive theoretical and empirical material related to design and use of the jet pumps in cryogenic systems operating by means of two-phase circulating helium.

4. Calculations for jet pumps

Fig. 5 shows a scheme for a jet pump. A computational technique specified to the conditions of liquid helium is designed and tested experimentally in [2, 3].

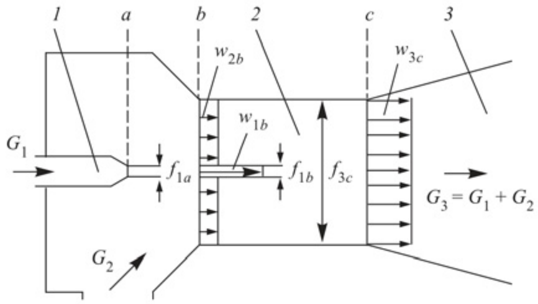

Fig. 5. Scheme of the jet pump. 1- the nozzle; 2 – mixing chamber; 3 – the diffuser

During device operation, a jet of compressed gas G_1 is accelerated in the nozzle, and, in further motion, carries away the injected flow G_2. In the mixing chamber, the speed of the flows are leveled. The mixed flow G_3 going out of the mixing chamber is expanded in the diffuser, its speed decreases, and the static pressure of the mixed flow increases up to the pressure of the stagnated flow.

Ratio of the mass flow of the injected helium to the mass flow of the operational helium is called the injection coefficient.

$$u = \frac{G_2}{G_1} \quad (1)$$

The theory of jet pumps is based on the equation for momenta and speed coefficients, which take into account the losses in various parts of the device. So-called characteristic equation for the jet pump pressure

$$\Delta p = p_3 - p_2 \quad (2)$$

can be obtained by solving the momentum equation for a cylinder mixing chamber combined with the Bernoulli equation and the continuity equation. The characteristic equation has a following form:

$$\Delta p = \frac{w_{1a}^2 f_{1a}}{V_{1a} f_{3c}} \left[\varphi_2 + u^2 \frac{f_{1a} V_2}{f_{2b} V_{1a}} \left(\varphi_2 - \frac{0.5}{\varphi_4^2} \right) - (1 + u^2) \frac{f_{1a} V_3}{f_{3c} V_{1a}} (1 - 0.5\varphi_3^2) \right] \quad (3)$$

where Δp is the jet pump head; p is the pressure; $\varphi_1 = 0.94, \varphi_2 = 0.97, \varphi_3 = 0.90, \varphi_4 = 0.92$ are the speed coefficients of the nozzle. the mixing chamber, the diffuser, and the entrance part of the mixing chamber, respectively ; G is the mass flow; w is the speed; f is the area of the cross section; and V is specific volume.

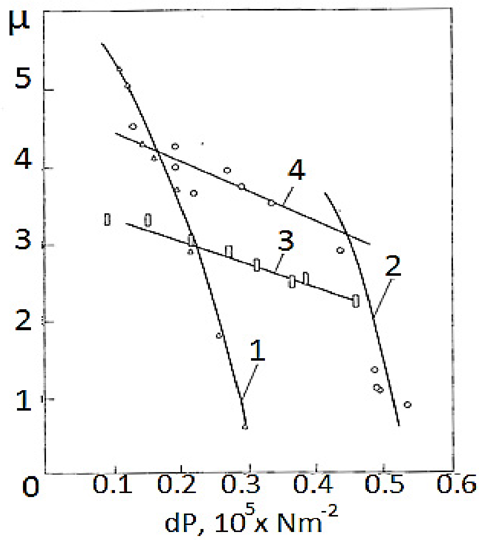

Fig. 6. Comparison of the experimented and calculate characteristics of jet pump. 1,2- calculation by the momentum equation; 3,4 – limiting modes; μ – injection coefficient, Δp – jet pump pressure rise

Fig. 6 shows the comparison of the experimental and calculate characteristics of jet pump. We have used a jet pump with the diameter of the cylinder mixing chamber equated to 3 mm. Despite the discrepancy, we have obtained an important result: the reached values of the mass flow for the injection flow have provided for a more stable operation of the superconducting magnet system of the accelerator, and reduced the power consumption.

5. General view of NICA cryogenics

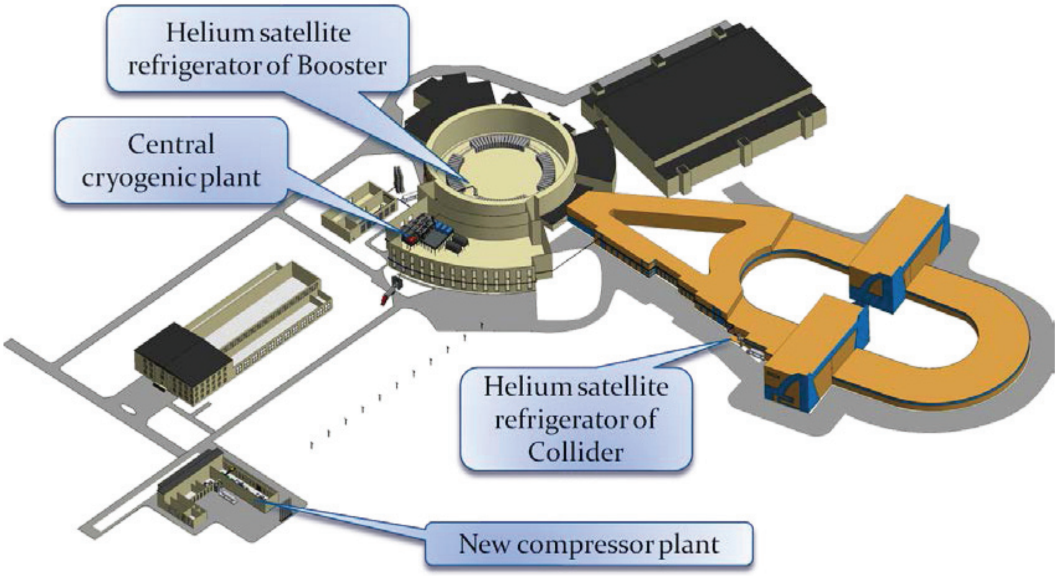

Fig. 7. General view of NICA cryogenics

The plans for the further development of the basic installations in the JINR Laboratory of High Energy Physics provided for the successive building of new accelerators: Booster and Collider, all using magnets with superconducting windings cooled to liquid helium temperatures. These two accelerators, combined with the existing Nuclotron in a single system, called NICA complex.

In the refrigeration of the future accelerators (Booster and Collider), cryogenic systems will consist of the central helium liquefier and "satellite" refrigerators located in close proximity to the accelerator rings. The "satellite" refrigerators operate using liquid helium obtained from the central liquefier. It makes possible to manage with minimum equipment in each of "satellite" refrigerators. In these case such refrigerator, which consists only of heat exchangers, is highly reliable, because the least reliable elements are concentrated in the central liquefier. Important features are that the system needs minimum cryogenics pipes and high thermodynamic efficiency is conserved. Jet pumps will be a one of the main parts of the cryogenic system of the future accelerators.

6. Conclusions

In this paper we showed the history of the development of the jet pumps at JINR, theoretical and empirical material we have accumulated over the years of developing and using a jet pumps, and also a results of operating. Moreover, we presented our plans to build a new accelerator NICA complex and to create a cryogenic system for it. The use of jet pumps allowed us to provide a reliable and effective cooling of the Nuclotron and to reduce the energy consumption because with the jet pumps there is no need to turn on the additional compressors like we had to do so in the case with the scheme without the jet pumps.

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