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Integrated design of an 18kW@4.5K/4kW@2K helium cryogenic refrigeration system for CiADS

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Abstract. Large cryogenic refrigeration systems are the only means to achieve a low-temperature environment for large scientific devices. As an important part of the China Initiative Accelerator Driven System (CiADS), an 18kW@4.5K/4kW@2K large helium cryogenic refrigerator is primarily used to cool down superconducting magnetic cryostats. It has been designed by Technical Institute of Physics and Chemistry, Chinese Academy of Sciences at the end of 2023. This paper gives an overview on the performance characteristics and working principle of the 18kW@4.5K/4kW@2K large helium cryogenic system. The integrated design of this helium cryogenic refrigerator is introduced. The overall engineering layout design based on the experimental building at Zhongshan Institute of Advanced Cryogenic Technology has been completed. The design result has been used to guideline the engineering and manufacturing phase. Its commissioning tests will be carried out and completed at the end of this year.

1. Introduction

Large-scale and even ultra-large-scale helium cryogenic refrigeration equipment can provide fundamental support for many large scientific devices, which are used in frontier basic research, high-tech applications, and other fields. At present, most large scientific devices utilize new types of superconducting accelerators equipped with superconducting main magnets or superconducting acceleration cavities. The use of these superconducting components can greatly reduce the size of accelerators and decrease their power consumption. Liquid helium and superfluid helium serves as main cooling mediums for achieving superconductivity. For modern large scientific devices, superfluid helium cryogenic systems are the mainstream direction of their cryogenic systems.

The term "megawatt-class large helium cryogenic refrigeration system" refers to a large-scale cryogenic system that has a cooling capacity of tens of kilowatts in the liquid helium temperature range and thousands of watts in the superfluid helium temperature range. Such systems are widely used in large scientific devices both domestically and internationally, such as the Shanghai High repetition rate XFEL and Extreme Light Facility (SHINE) [1]; the High Intensity Heavy-Ion Accelerator Facility (HIAF) [2]; the Circular Electron Positron Collider (CEPC) [3]; the European Organization for Nuclear Research's Large Hadron Collider (LHC) [4]; the European X-ray Free Electron Laser (E-XFEL) [5]; the Continuous Electron Beam Accelerator Facility (CEBAF) [6]; and the European Spallation Source (ESS) [7], etc.

The China Initiative Accelerator Driven System (CiADS) project, which is undertaken by the Institute of Modern Physics of the Chinese Academy of Sciences, utilizes superconducting linear accelerator technology in its heavy ion linear accelerator [8]. The superconducting section contains a total of 31 cryostats with five different cavity types, spanning approximately 250 meters in length, and employs a 2K superfluid helium immersion cooling method. The superconducting cavities are cooled by a helium refrigeration system with an equivalent cooling capacity of 18kW at 4.5K (including 4kW at 2K).

2. Performance characteristics and working principle of the 18kW@4.5K/4kW@2K system

2.1 Performance characteristics and system structure composition

Based on the cooling capacity and cooling output modes required by CiADS for its cryogenic system, the process design for an 18kW@4.5K/4kW@2K large helium cryogenic refrigerator has been completed. According to the design results, the performance characteristics of this system are shown in Table 1.

Table 1. The performance characteristics of 18kW@4.5K/4kW@2K helium cryogenic refrigerator

Work mode	2K heat load [W]	4.5K heat load [W]	4.5-75K heat load [W]	4.5-20K heat load [W]	50-75K heat load [W]	Equivalent heat load [W]
2K mode	⩾5000	--	⩾5000	--	⩾15000	⩾5400@1.8K
4.5K mode	--	⩾4000	--	⩾24000	⩾15000	⩾18000@4.5K

The schematic diagram of the 18kW@4.5K/4kW@2K large helium cryogenic refrigerator is shown in Figure 1. The system consists of a compressor unit, a gas management system, a cold box, a 4K Dewar, a 2K simulated load, cryogenic transfer lines of liquid helium and liquid nitrogen, room temperature pipelines of helium, room temperature valves and a control system, etc. Additionally, the cold box includes turbine expanders in five groups, four cold compressors, multi-stage cryogenic heat exchangers, 80K and 20K cryogenic absorbers, and cryogenic valves, etc. The compressor unit includes a high-pressure compressor group, a medium-pressure compressor group, and a negative-pressure compressor group. The gas management system includes a medium-pressure bypass valve, a low-pressure bypass valve, a loading valve, an unloading valve, and a helium buffer. By controlling the opening of these valves, the system's pressure can be kept stable.

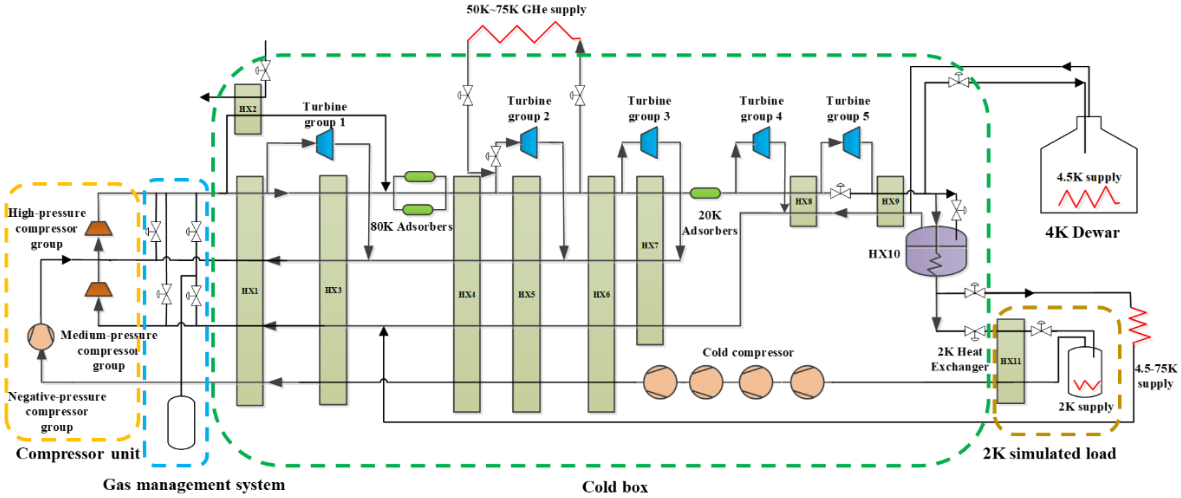

Figure 1. The schematic diagram of 18kW@4.5K/4kW@2K large helium cryogenic refrigerator

2.2 working principle of the system

The compressor unit is composed of three stages of compressor groups, each responsible for a specific pressure range. The medium-pressure compressor group compresses helium from 1.05 bar to 4.05 bar. The high-pressure compressor group further increases the pressure from 4 bar to 19 bar. The negative-pressure compressor group finish the compression process from 0.36 bar to 4.05 bar. Together with the gas management system, the compressor unit ensures system stability across high, medium, and low pressures.

High-purity helium gas from the outlet of the high-pressure compressor group enters the high-pressure side of the cold box. Inside the cold box, it undergoes liquefaction through liquid nitrogen pre-cooling, three-stage turbine expansion cooling, and a single-stage throttling process, utilizing the latent heat of vaporization of liquid helium to provide a cooling capacity of 4.45K (1.25bara). Before throttling, an additional boost turbine is added to reduce exergy loss and increase the liquid content in throttling, in order to improve the system's energy efficiency. The liquid nitrogen pre-cooling stage is paralleled with a single-stage turbine expander. When liquid nitrogen is not available, the system defaults to the turbine expander. Conversely, if liquid nitrogen is accessible and economically priced, we opt to utilize it, halting the turbines to reduce helium flow from the compressor, thereby conserving electrical consumption.

When the cryogenic refrigerator operates in liquefaction mode, the 4K Dewar is used for gas-liquid separation after throttling. The saturated liquid enters the Dewar for storage, while the saturated gas returns to the low-pressure side. When the cryogenic refrigerator operates in cooling mode, the low-temperature helium gas from the final heat exchanger’s outlet is divided into two streams. One stream is throttled to form a two-phase gas-liquid mixture that enters the subcooler’s shell side. The other stream enters the tube side, where it utilizes the saturated liquid helium formed by throttling to produce subcooled helium output. It then throttles into the 2K simulated load Dewar, achieving 2K cooling output through evacuation and depressurization by the cold and negative-pressure compressors. Additionally, the helium refrigerator supplies 50K helium gas to cool the cold shield and the superconducting magnet current leads of user’s cryostats and transfor lines. This gas flow returns to the refrigerator’s cold box at 75K. Furthermore, the helium refrigeration cycle also provides subcooled liquid helium to cool the user's cryostat of the 4.5K superconducting cavity coupler. This gas flow returns to the cold box’s low-pressure side at 75K@1.1bara.

3. Integrated design of 18kW@4.5K/4kW@2K system

3.1 Integrated design process of the system

The integrated design process flowchart of the 18kW@4.5K/4kW@2K large helium cryogenic refrigerator is shown in Figure 2. This system features complex subsystems, such as the compressor station and the cold box, which have intricate structures and numerous interfaces. The goal of system integration design is to ensure these subsystems work in harmony, creating an efficient and cohesive unit that meets the refrigerator’s overall performance indicators, including cooling capacity, cooling temperature, and power consumption.

The thermal parameters established in the process design report of the 18kW@4.5K/4kW@2K system guide the selection and configuration of compressor unit. Design calculations are necessary for turbine expanders, cold compressors, and heat exchangers, while cryogenic valves require careful design selection. Based on these, the cold box design will be completed.

System integration design also involves obtaining design parameters from each subsystem to determine the refrigerator’s dimensions, installation space, and utilities requirements, including water, electricity, and gas. This information is then used to design and select the necessary utility systems, including the storage tank system, cooling water system, and instrument air system.

To meet the refrigerator system’s final performance indicators, a thorough understanding of each subsystem’s design, structural, and process parameters is essential. It is necessary to establish the interface parameters, structural, and functional relationships between different subsystems and with utility systems. This ensures well-difined boundaries and compatible interface parameters between each subsystem. With these foundations, the overall layout design of the system will be carried out, and the design and connection of all pipelines will be completed. If the pipelines’ working pressure meets the pressure pipeline standards, a qualified third party is required to design and draw the engineering diagrams. Finally, the system’s integration engineering design is finished.

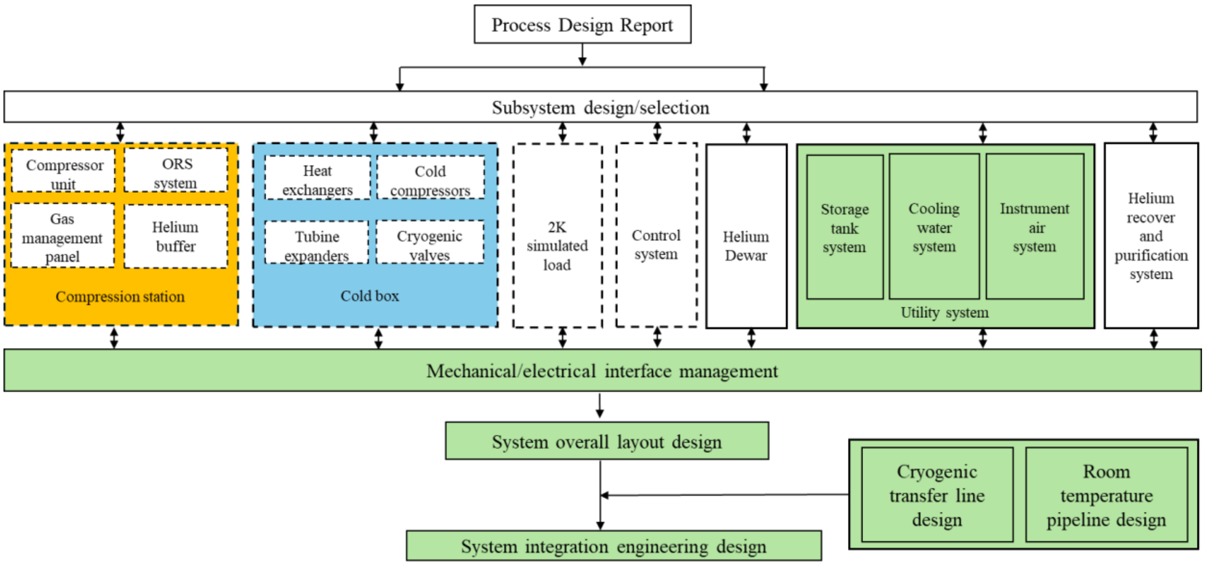

Figure 2. The integrated design process flowchart of the 18kW@4.5K/4kW@2K large helium cryogenic refrigerator

3.2 System's integration engineering design

Once the design or selection of all subsystems for the 18kW@4.5K/4kW@2K system is completed, its overall layout design can be carried out. Due to the significant noise generated by the compressors and the gas management panel, these components, including ORS system, are all placed in a soundproof room. Helium buffers are located outside this room. To minimize noise impact on commissioning persons, the cold box is placed near the control centre, which is distant from the soundproof room. The 4K Dewar and 2K simulated load are located in close to the cold box within the same room. The liquid nitrogen tanks are placed outside the cold box room to supply the nitrogen nearly. The utility systems are placed near the compressors, within another soundproof room. Room temperature pipelines connect the compressor unit, cold box, helium buffers, helium recovery and purification system, and the instrument air system. Cooling water is transported through its pipelines to the compressor unit, turbine expansion unit, and cold compressor unit for cooling the equipment. Liquid nitrogen transfer pipelines connect the liquid nitrogen tanks and the cold box. Liquid helium transfer pipelines connect the cold box and the 4K Dewar. Multi-channel cryogenic transfer pipelines connect the cold box and the 2K simulation load. The high-pressure pipe connecting the compressors to the ORS system, and the high-pressure pipe connecting the ORS system to the cold box must comply with local legal regulations. These pipes have been designed by a qualified company to meet these standards. The overall layout design of the 18kW@4.5K/4kW@2K system is shown in Figure 3.

The integration engineering design of the 18kW@4.5K/4kW@2K system has been completed, and we have obtained all necessary engineering drawings from a qualified company. The design result has been used to guideline the engineering and manufacturing phase. Its commissioning tests will be carried out and completed at the end of this year.

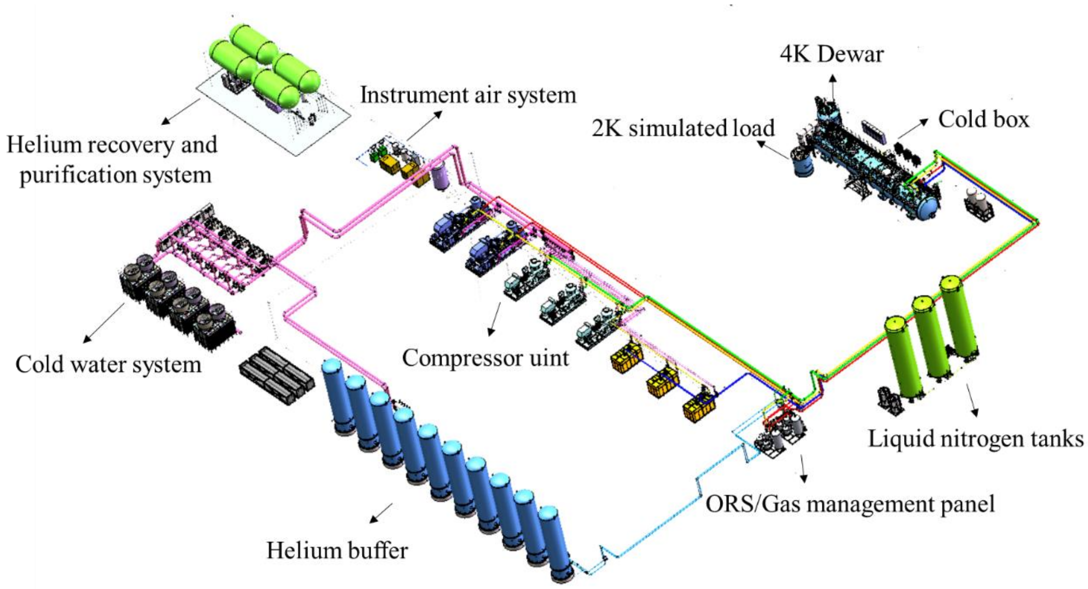

Figure 3. The overall layout design of the 18kW@4.5K/4kW@2K system

3.3 Design results of the compressor unit and the cold box

Screw compressors have the characteristics of high reliability, few components, and no vulnerable parts. They operate reliably and have a long lifespan. Generally, the design lifespan of screw compressor heads can reach up to 30 years. As a common type of gas compressor, they are widely used in modern helium refrigerators around the world. In our 18kW@4.5K/4kW@2K system, we employ helium injection screw compressors. The design parameters of the compressor unit are shown in Table 2.

Table 2. The design parameters of the compressor unit

Parameter	High-pressure compressor group	Medium-pressure compressor group	Negative-pressure compressor group
Supply voltage (V)	10k	10k	380
Pressure (bar)	4 -19	1.05 - 4.05	0.36 - 4.05
Motor power of one machine (kW)	2240	450	375
Cooling water flowrate of one machine (t/h)	374	18	12

The cold box is composed of turbine expanders in five groups, four cold compressors, multi-stage cryogenic heat exchangers, and many cryogenic valves, etc. The turbines are supported by a bearing system with the turbine wheel at one end and the compressor wheel at the other end, with isentropic efficiencies as high as 70%. The heat exchangers uesd in our system are aluminium alloy plate and fin types. The cold compressors are centrifugal, featuring active magnetic bearing systems, with isentropic efficiencies reaching up to 65%. After completing the design of these components, the cold box designe can be carried out. Due to the large number and size of heat exchangers inside the cold box, along with the large pipeline specifications, the 18kW@4.5K/4kW@2K helium refrigeration system's cold box uses a horizontal structure. The internal components have been modularized based on the PID design results, facilitating sectional installation of the equipment. The cold box's final dimensions are 4.2 meters in diameter, 27 meters in length, and 5 meters in height.

3.4 Design results of the utility systems

The 18kW@4.5K/4kW@2K system is confirmed to complete system integration and commissioning at the experimental building of Zhongshan Institute of Advanced Cryogenic Technology (ZIACT). As the factory is newly construted, the utility systems require design and installation. The design parameters for these utility systems are shown in Table 3.

Table 3. The design parameters of utility systems

Description	Unit	Data
Cooling water flowrate	m^3/h	~1330
Cooling water temperature	℃	<16
Cooling capacity	kW	~7000
Instrument air flowrate	m^3/min	~32
Instrument air pressure	MPa	>0.6
Volume of liquid nitrogen tank	m^3	~300
Pressure of liquid nitrogen supply	MPa	0.3
Volume of helium buffer	m^3	~1000

3.5 Safety design of the system

The 18kW@4.5K/4kW@2K system involves hazardous factors such as high pressure (1.9MPa), low temperature (2K), strong electricity (compressor power supply of 10kV and 380V), and high temperature (compressor oil cooler temperature is greater than 60℃) during operation. Therefore, we entrust a third party to conduct hazard and operability analysis (HAZOP analysis). By the result of analysing, we can find the main hazards and influencing factors in the working process, and then take measures to improve the system design. In addition, when designing the control system, we establish necessary interlock protection measures to ensure the safety of personnel and machines.

4. Conclusion

To meet the requirements of CiADS, this paper gives an overview on the integrated design of an 18kW@4.5K/4kW@2K large helium cryogenic refrigeration system. Based on our design, this system can supply cold capacity at 2K, 4.5K, 4.5K to 75K, and 50K to 75K, to satisfy different application scenarios of CiADS. In order to complete its integration design, the integrated design process is planned, with the designs for the compressor unit, cold box, utility systems, and other components completed. Finally, the overall engineering layout design of this helium cryogenic system has been completed. The design result has been used to guideline the engineering and manufacturing phase. Its commissioning tests will be carried out and completed at the end of this year.

5. References

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