A Long-Life, High-Capacity and High-Efficiency Cryogenic System Developed for High-Tc Superconducting Magnet Applications

Renjun Xue, Jun Tan, Tao Zhang, Yongjiang Zhao, Bangjian Zhao, Han Tan, Yujia Zhai, Shiguang Wu, and Haizheng Dang

***Abstract*—Cryogenic system plays a vital role in the field of high-Tc superconducting (HTS) magnet applications. For a variety of HTS magnet applications in energy storage devices, current limiters, generators, and maglevs, the technology itself is relatively mature. However, the problems associated with the used cryocoolers have hampered the advancement of their practical applications. At present, China is developing a new generation of electrodynamic suspension prototype train with HTS magnets. Compared with the existing commercial electromagnetic suspension technology, it has better suspension stability, larger suspension gap, and lower energy consumption. To meet the aimed cooling requirement of the vehicle-mounted HTS magnet, a long-life, high-capacity and high-efficiency cryogenic system based on the Stirling-type pulse tube cryocooler (SPTC) is designed and developed in the authors' laboratory. The SPTC driven by the linear compressor without any moving component in the cold head has the intrinsic merits of long life and high reliability. The cryogenic system can achieve a minimum no-load cooling temperature of 12 K. Multiple SPTCs will provide a cooling capacity of 100 W at 45 K with the relative Carnot efficiency of 10.8 % to cool the HTS coils inside the magnet. This paper will describe and analyze the overall design approach, integration with the HTS magnet and the arrangement in maglev of the developed cryogenic system, together with the performance characteristics of the SPTC during the laboratory test.**

***Index Terms*—Cryogenic system, High-Tc superconducting Magnet, Stirling-type pulse tube cryocooler, Long MTTF, Vehicle-mounted application.**

I. Introduction

SINCE superconductivity was discovered by H. K. Onnes in 1911 [1], superconducting application has attracted extensive attention for its superior properties. High-Tc superconducting (HTS) magnet technology is widely applied in energy storage devices, current limiters, generators, accelerators and maglevs [2]–[6], etc. To ensure that the HTS facilities work properly and steadily, the cryogenic system becomes one of the key supporting equipment.

At present, China is developing a new generation of electrodynamic suspension (EDS) train with vehicle-mounted HTS magnets. Compared with the existing commercial electromagnetic suspension (EMS) technology in Shanghai maglev, superconducting maglev has the unique advantages of excellent levitation and guidance stabilities, larger suspension gap, and lower energy consumption which makes it a promising candidate for the future 600 KPH ultrahigh-speed ground transportation. As a vital component of the superconducting maglev, the HTS magnet in its linear synchronous motor works in an environment lower than 45 K. In other words, the performance of the HTS magnet is directly determined by the efficiency and reliability of the cryogenic system, which becomes a research focus in practical development. Cryogenic system equipped for the vehicle-mounted HTS magnets needs to have the following characteristics: low power consumption, low maintenance, compact structure, high efficiency, and high reliability under high-intensity magnetic field environment.

Superconducting components are typically cooled by immersion in cryogen, heat exchange with cryogen condensed from cryocooler, or direct heat conduction with cryocooler [7]–[10]. Several types of cryocoolers such as GM cryocooler, Stirling cryocooler, and pulse tube cryocooler are usually regarded as the possible cryocoolers for the magnet cryogenic system [11]–[14]. Stirling-type pulse tube cryocooler (SPTC) driven by the linear compressor without any moving component in the cold head keeps the intrinsic merits of long life and high reliability, and thus is an ideal choice. To meet the target cooling requirement of the vehicle-mounted HTS magnet, a long-life, high-capacity

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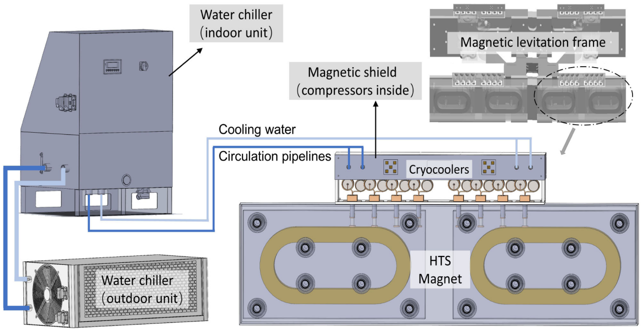

Fig. 1. Overall design of the developed cryogenic systems in Maglev.

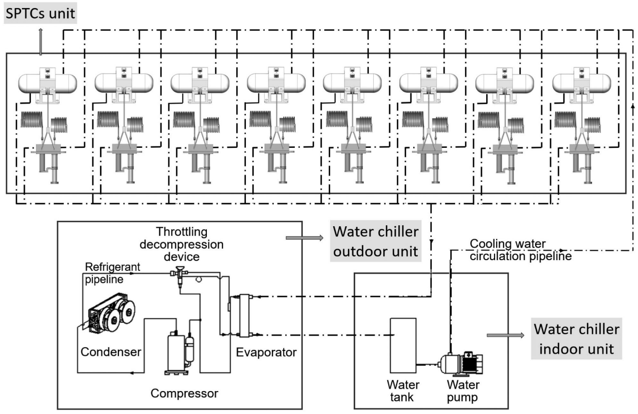

Fig. 2. Schematic diagram for the Components of the system.

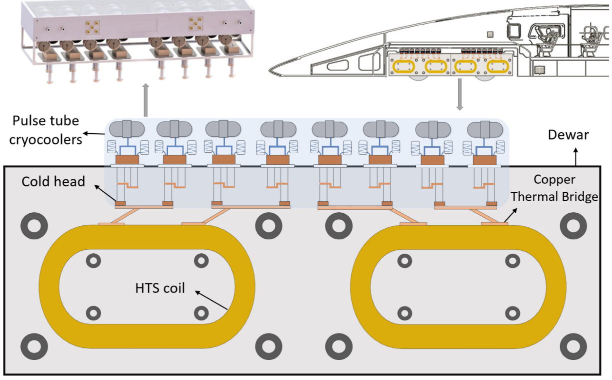

Fig. 3. Coupling structure of the cryogenic system for the HTS magnet.

and high-efficiency cryogenic system based on the SPTCs from space cryogenic technology in the authors' laboratory [15]–[17] is designed and developed.

The cryogenic system with multiple SPTCs aims to achieve a cooling capacity of 100 W at 45 K for cooling the superconducting coils inside the HTS magnet and reach a minimum no-load cooling temperature of 12 K. The overall design approach, coupling and integration of the cryogenic system for the HTS magnet and the arrangement in maglev will be described and analyzed. Meanwhile, the performance characteristics of the developed cryocooler applied in the cryogenic system during the laboratory test will be presented and discussed.

II. CRYOGENIC SYSTEM USING THE SPTCS

A. Design of the Integrated Cryogenic System for HTS Maglev

The levitation frame of the HTS maglev is one of the key components to maintain the suspension of the train body. According to the current design, there are four HTS magnets on a levitation frame, and each magnet has two coils winded with the second-generation superconducting REBCO wire. For the coils, they typically need a working temperature below 45 K to make for sufficient performance, so that the magnet can generate enough magnetic field to maintain the suspension and propulsion of the train. As is shown in Fig. 1, All the magnets work independently, and each is equipped with 8 SPTCs to cool the coils inside. The SPTCs are arranged above the magnet surface.

In addition to cryocoolers in cryogenic systems, water chiller is also an indispensable and important part. In the designed system, a high-power water chiller is configured for providing the cooling capacity of 24 kW with the outlet water temperature of 15 °C and the ambient temperature of 35 °C, for 32 SPTCs in a levitation frame with 4 HTS magnets. The water chiller is connected to the integrated module of the cryocoolers above each magnet through the cooling water circulation pipelines. After fully heat exchanging with the main heat-dissipating components including the compressor shell and the cold head's hot end heat exchanger in SPTC, cooling water returns to the water chiller for re-cooling.

For the purpose of making full use of the space and creating a quiet and comfortable environment inside the maglev train, the water chiller adopts a split arrangement depicted in Fig. 2. To utilize the space inside the train carriage, a water chiller indoor unit is arranged, which mainly includes the display panel, circuit interface, water injection port, water tank, cooling water circulating pipeline, and silent water pump. The outdoor unit is hoisted at the bottom of the carriage, and the main refrigeration components are integrated inside the outdoor unit, consisting of the condenser, evaporator, compressor, throttling decompression device and refrigerant pipeline. The low-temperature refrigerant exchanges heat in the evaporator with returned water from the cooling water pipeline and then cools the water to the temperature setting for cooling cryocoolers.

B. Design of the SPTCs Module and Coupling Structure With the Magnet

1) Composition of the SPTCs Module: It can be seen from Fig. 3 that an HTS coil is cooled by 4 SPTCs, which means that a magnet module containing two coils will be equipped with 8 SPTCs. The SPTCs are symmetrically distributed on the upper surface of a single magnet, and each pulse tube cryocooler has a modular design for convenience to install and disassemble during routine maintenance work. Both the compressor and the cold head can be disassembled and replaced independently, and connected by a flexible connecting pipe for transferring pressure waves.

2) Cold Head and Coupling Structure: Generally, Direct cooling and indirect cooling are the two common ways to cool the magnet coils. In a direct cooling system, the cryocooler's cold head is directly connected with the low-temperature components of the superconducting magnet through a thermal connector. Heat conduction is the main way for heat transfer during the cooling process. This type of cooling system has no dependence on cooling media with the advantages of simple structure, high heat exchange efficiency, and low power consumption. While in the indirect cooling system, cryocoolers and superconducting devices are arranged separately, the cooling media (using low Tc working fluid like He & N_2) cooled by the cryocoolers is transferred through the cryogenic fluid circulation pipelines to cool the superconducting devices. This type of system has the most prominent feature to be able to realize the long-distance arrangement between the cryocoolers and the magnets which is a suitable choice for medium-sized cryocoolers with larger cooling capacity or superconducting devices with moving components. But at the same time, the equipment such as the low-temperature fluid transmission pipelines, cryogenic pump and filter will increase the construction cost and space occupation, and also bring in additional cooling capacity loss. As a result, the overall cooling efficiency of the direct cooling system is relatively higher than that of the indirect cooling system so that direct cooling is used in the designed cryogenic system for maglev.

In view of the vehicle-mounted magnets manufactured by the second-generation superconducting REBCO wire working in a low-temperature environment below 45 K, the designed cryogenic system adopts the technical route of directly cooling by using thermal bridges to connect the magnet coils and the SPTCs' cold heads. Above each magnet is the cryocoolers module integrating 8 SPTCs. Each coil is cooled by 4 SPTCs to work below 45 K. The cryogenic components are wrapped with the multilayer insulation material as the insulation method for blocking the cryogenic heat load from the ambient temperature. Under the cryogenic environment, the HTS magnet can set up a high magnetic field for the linear synchronous motor. This ensures the demands of the levitation and propulsion system for the maglev train.

Thermal bridges manufactured from pure copper with high thermal conductivity are employed to connect the SPTCs' cold heads and the HTS coils to make heat exchange mainly by the way of heat conduction. As illustrated in Fig. 3, multiple thermal bridges are installed between the coils and the cold heads, which makes the cooling power generated by the SPTCs more uniformly distributed to the two coils inside the magnet. In this way, the two coils work under the same cooling conditions to ensure that the two coils can have similar superconducting properties in the cryogenic environment.

C. Merits of the Designed Cryogenic System With SPTCs

Vehicle-mounted applications in the field of high-speed transportations like maglev put forward special requirements for the used cryocoolers and cryogenic systems. The merits of the designed cryogenic system with the SPTC in Fig. 4 will be described in detail below.

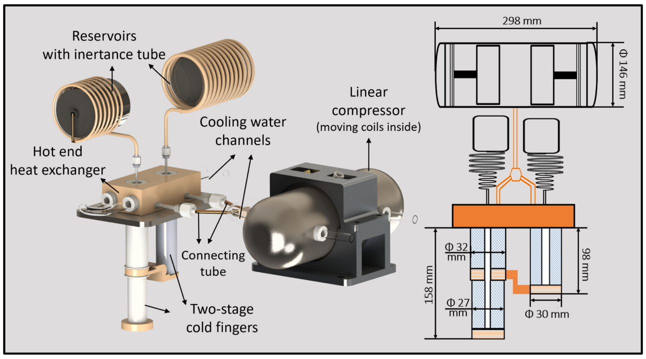

Fig. 4. Outline and composition of the SPTC.

1) Characteristics and Superiorities of the SPTCs: The pulse tube cryocooler adopts a modular design, so the compressor, connecting pipe and cold head can be assembled and disassembled independently. The moving coil linear compressor is the only mechanical part in the SPTC, and it produces a low noise level below 45 dB during operation. As the SPTC's cold head has no moving part inside, it eliminates the wear-out and maintains the low vibration force of $\leq 0.1\ \mathrm{N_{RMS}}$.

In addition, the SPTC is developed and manufactured in accordance with aerospace application standards, so that keeps high reliability and efficiency under the ultra-fast driving condition and has the expected long service time with the main time to failures (MTTF) of more than 5 years. The mechanical vibration frequency of the SPTC is designed differently from the vibration frequency of the maglev train during the high-speed operation to prevent the damage caused by resonance.

2) Advantages of the Designed Cryogenic System: According to the key demands of on-board equipment for Maglev, the designed cryogenic system owns various advantages as followed.

Firstly, since the cryogenic system uses small-sized SPTCs, it can achieve light weight and compact structure. The installation of compressors and cold heads can be flexibly arranged according to the spare space near the HTS magnet.

Secondly, the application of SPTCs inherited from space technology makes the cryogenic system achieve long operating time and long lifetime, so it also has a long maintenance-free period. This outstanding feature reduces the maintenance cost and difficulty in practical engineering applications.

Thirdly, as the corollary equipment of HTS magnets, it is inevitable that some of the components in the cryogenic system will work under high magnetic field intensity, which imposes requirements for the magnetic field adaptability or magnetic shielding. The cold heads of the SPTCs show excellent electromagnetic compatibility characteristics under high magnetic flux density above the HTS magnet. They can be directly installed on the magnet surface. The compressors with driving motors inside are integrated into a shell made of materials with high magnetic absorption properties to ensure that they work in a low-intensity magnetic field environment.

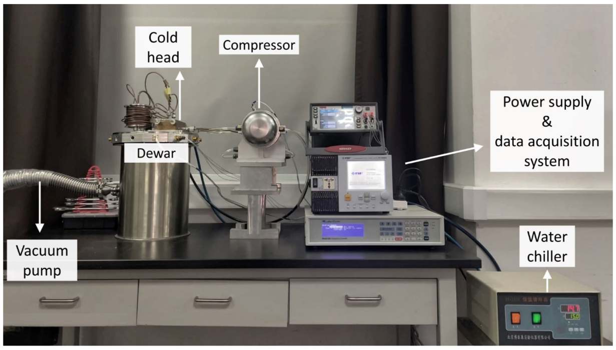

Fig. 5. Schematic of the SPTC's experimental test.

What's more, the SPTCs have high cooling efficiency and low input power, which are beneficial to reduce the energy consumption of the entire maglev train. Finally, using multiple SPTCs can enhance the stability and reliability of the system. During the operation of the magnet, if one SPTC accidentally fails, others will continue to work. It can prevent the sudden loss of the cooling power from causing a sharp temperature increase of the HTS coil. Meanwhile, it is a simple way to expand the cooling capacity for the cryogenic system as well.

III. Performance Characteristics

A. Method and Configuration of the Experiment

In order to test the cooling capacity of the SPTC in our designed cryogenic system, thermal resistance is installed on the second-stage cold finger to simulate the heat load in the experiment. Based on the thermodynamic equilibrium theory, the cooling capacity at different cooling temperatures is measured by adding heat load to the cold finger.

As shown in Fig. 5, the cold head is installed in the Dewar. During the experimental test, the Dewar is connected to a turbomolecular pump to keep the vacuum constant. The water chiller provides cooling water for the hot end heat exchanger of the cold finger and the compressor shell to bring out the internal heat and guarantee the stable operation of the SPTC. A power source is used to supply electricity to the compressor, and another power meter is applied to control the heat output of the thermal resistance. The data acquisition system can detect the real time temperature of the cold finger.

The initial parameters of the experiment are as follows: the working fluid is high-purity helium gas; the charging pressure is 2.8 Mpa; the working frequency of the power input is 48 Hz; the temperature of cooling water is 15 °C.

B. Experimental Performance

By gradually adding heat load by the thermal resistance, the cooling capacity of the second-stage cold finger under different cooling temperatures is measured with the input power of 625 W from the linear compressor. The cryocooler is tested for several more hours to investigate the stability.

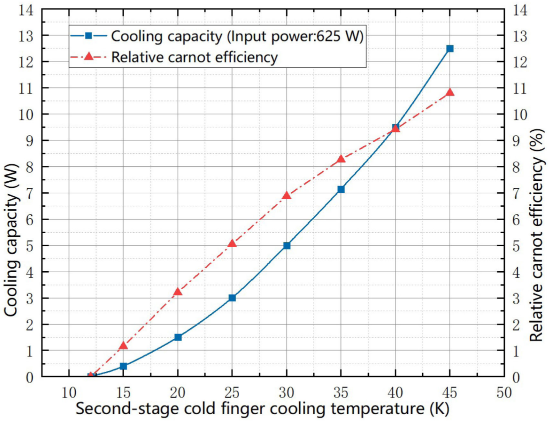

Fig. 6. Experimental results of the SPTC in the cryogenic system.

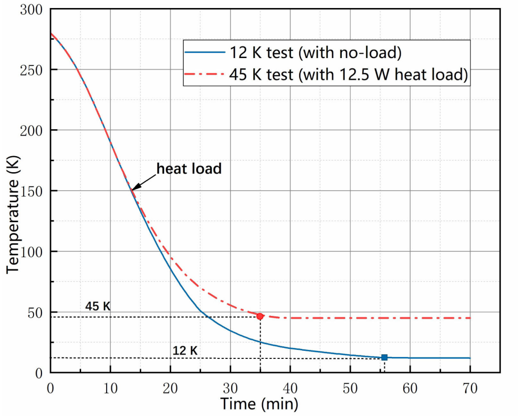

Fig. 7. Cooling curves for the cryocooler in the test.

Fig. 6 shows the cooling capacity and relative Carnot efficiency of the second-stage cold finger within the working temperature range of the HTS magnet. The minimum temperature with no cooling capacity is 12 K. While under the working temperature of 45 K, the cold finger generates 12.5 W cooling power with a relative Carnot efficiency of 10.8 %. The experimental result indicates that our designed cryogenic system with 8 SPTCs is able to provide a cooling capacity of 100 W@45 K which can meet the cooling demand for one HTS magnet.

Fig. 7 shows the cooling curves of the whole system. It takes about 35 minutes to cool down to 45 K when a heat load of 12.5 W is added to the cold finger of the SPTC. Also, the system is tested with no heat load. The process takes 56 minutes to cool down to 12 K.

IV. Conclusion

This paper presents the development and testing of a long-life, high-capacity and high-efficiency cryogenic system based on the SPTC developed for the high-Tc superconducting magnet in maglev applications. The overall design approach and the integration schematic of the cryogenic system coupled with the HTS magnet are analyzed in detail. Meanwhile, the performance characteristics during the laboratory test indicate that the cryogenic system with 8 SPTCs can typically achieve a cooling capacity of 100 W at 45 K with the relative Carnot efficiency of 10.8 % and be a promising and attractive candidate to cool the on-board HTS magnet. Since the developed system is inherited from our well-proven long-life space cryogenic technology, its mean-time-to-failure (MTTF) is expected to reach 5 years. The above performance indicates that the developed cryogenic system can meet the demand for cooling the vehicle-mounted HTS magnet. Further verification of the long-life performance is underway.

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