Levitation Performance of YBCO Bulks in Super-cooling Condition under a Low Pressure Environment

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*Abstract*—Taking the influence of low pressure on levitation performance of high temperature superconducting (HTS) maglev into account, we established a simple super-cooling platform based on pumping method to study the levitation performance of YBCO bulks above the Halbach permanent magnet guideway (PMG) under different pressure conditions. Through measuring the temperature of liquid nitrogen (LN2) during the decreasing process of pressure, it is known that the LN2 would turn into a super-cooling state as the pressure reduction. Measurements of the levitation force versus vertical motion and the force relaxation were performed both in case of zero-field-cooling (ZFC) and field-cooling (FC). The experimental result showing that, the decreasing pressure is beneficial to improve the levitation performance of HTS bulks, and the maximum force increase up to 23.5% and 22.1% were realized in ZFC and FC compared with the atmospheric pressure, respectively. Moreover, the low pressure could also reduce the hysteresis loop area and restrain the relaxation decay of levitation force. These results imply that, the low pressure environment in evacuated tube will be beneficial to the levitation performance of HTS maglev system.

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*Index Terms*—high temperature superconductor, Maglev, low pressure, super-cooling, levitation performance

# I. Introduction

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aking advantage of the novel property of self-stable levitation in an inhomogeneous magnetic field, high temperature superconducting (HTS) maglev has a tremendous potential in the domain of transportation, and the vehicle prototypes have been developed in China [1], Germany [2] and Brazil [3] successively. Without mechanical contact, the maglev vehicle can achieve a higher speed level. Recently, the highest speed of 603 km/h has been realized in Japan using the electrodynamic levitation technique [4], and this remarkable achievement demonstrates that the maglev equips ability of high-speed transport. However, there is still an inevitable factor impeding the new traveling vehicle further raising speed, which is the air resistance [5]. By contrast, the airplane can reach the speed of about 900 km/h mainly benefiting from low air resistance in the sky. Aiming to eliminate the obstacle of dense atmosphere, the evacuated tube transportation (ETT) is an efficient and ideal solution. In 2014, an Evacuated Tube High-Temperature Superconducting Maglev prototype [6] has been completed in our group to carry out relevant research about the operation state of levitation system under low pressure environment. Before this, related article has proposed the feasibility of ETT system, and pointed out the superiority of HTS maglev in the system [7], [8]. But while the low pressure environment providing the key function for speed improvement, there are some potential problems coming out and needing to be studied.

The liquid nitrogen (LN2) as refrigerant to ensure the superconducting state of superconductor, the influence of low pressure on it is a key point. Previously, related work has investigated that the low pressure environment is in favor of retarding the evaporation rate of LN2 [9]. This study gives a reference for estimating the safe operation time of HTS maglev. Moreover, the low pressure environment will cause the decrease of LN2 temperature and reduce the convection and the radiation heat [10]. As the decrease of LN2 temperature, the superconductor turns into super-cooling state and its levitation performance interacting with the applied magnetic field has an effective improvement [11]. For the temperature dependence of levitation performance in the HTS levitation system, related work have been carried out by employing the refrigerator to realizing different temperatures under 77 K. Results show that, the levitation performance of HTS bulk presents a superior state in a low temperature under 77 K [12]-[16]. However, for the maglev system using the cooling approach of LN2 cryogen soaking, it is still necessary to investigate the relationship with pressure, LN2 temperature and levitation performance with regard to the ETT system.

In this article, a simple super-cooling platform based on pumping method was set up to realize the adjustable pressure environment for simulating the operating condition of HTS maglev inside the ETT system. Based on this platform, we undertake a systematic study about the levitation force and force relaxation of YBCO bulks in both conditions of LN2 (77 K) and super-cooling nitrogen under different pressures. Consequently, this work can offer a basic reference and make a prediction about the levitation performance of HTS maglev running in a low pressure environment.

# II. EXPERIMENTS

Taking the HTS maglev ring test line [17] as study background, we employed the same type HTS bulk with the test line and a set of Halbach permanent magnet guideway (PMG). The rectangular three-seeded HTS bulks were made by the ATZ GmbH (Germany), which have superior performance across the seeds [18], [19]. There were four HTS bulks and the size of each bulk was 64 mm, 32 mm and 13 mm in length, width and thickness, respectively. The transvers area of the PMG is 4500 mm2, and the arrangement of four bulks is schematically presented in Fig. 1.

**FIG. 1 HERE**

Fig. 2 shows a schematic drawing of the experimental setup. The HTS maglev measurement system SCML-1 was used to measure the levitation force and the force relaxation, while the detail depiction of this system was presented elsewhere [20]. Aiming to obtain the LN2 with super-cooling state, a simple super-cooling platform was established in-house. The platform comprised a vacuum chamber, a sliding vane vacuum pump (2XZ-2), a scroll vacuum pump and a vacuum meter. As shown in Fig. 2, the vacuum chamber was installed on SCML-1, which not only acted as a vacuum chamber, but also played a role of LN2 container and was used to fix the HTS bulks. The bottom thickness of the chamber is 11 mm, while the minimum measurement gap between its bottom surface and the top surface of PMG is 1 mm. Hence, the minimum distance between the HTS bulks and the PMG is 12 mm. The vacuum pumps were connected with the chamber to sustain a setting pressure value in the experiment. To collect the temperature data of LN2 during the evacuation process, Lakeshore Model 331 temperature controller was introduced and coordinated with the PT100 resistance sensor.

**FIG. 2 HERE**

Before the experiments of levitation performance measurements, we detected the LN2 temperature under different pressure states during a continuous pumping process, with filling LN2 into a cylindrical foam box putting in the chamber. It was founded that, when the pressure inside chamber lowered than 20 kPa, the LN2 appeared solidifying phenomenon gradually from periphery to the center of box. Considering the fluidity of solid nitrogen is poorer than LN2, which is harmful for the HTS maglev system, we propose to introduce the differential vacuum valve in the practical application to keep the pressure inside cryostat above value of 20 kPa, avoiding the appearance of solid nitrogen. For research in this paper, the lowest pressure was chosen as 25 kPa. Four kinds of pressure conditions were selected in the experiment, 100 kPa (atmospheric pressure), 65 kPa, 45 kPa and 25 kPa, respectively.

The experiment was conducted both in zero-field-cooling (ZFC) and field-cooling (FC) types, and the whole process of each type included four steps. The first step was the cooling of HTS bulks, while bulks kept a special distance from the PMG surface and this step would last 15 minutes. The heights of bulks above the PMG were 60 mm and 30 mm for the ZFC regime and the FC regime, respectively. After that, we used the sliding vane vacuum pump and the scroll vacuum pump to evacuate vacuum chamber to one of the chosen pressure value. The bulks needed to be further cooled for 5 minutes under the above pressure condition. Subsequently, the third step was the levitation force measurement. In this step, for the ZFC regime, the bulks moved vertically from 60 mm to 12 mm height above the PMG and then back to the height of 60 mm. While for the FC regime, the bulks moved to the height of 60 mm from the PMG and then the measurement were implemented similarly to the ZFC case. The levitation force data was measured and recorded per millimeter, and the movement speed of bulks was 2 mm/s. Finally, straight after the force measurement, the bulks were moved down to the 12 mm position away from PMG to measure the force relaxation for 300 s.

# III. RESULTS AND DISCUSSION

Fig. 3 presents the measured temperature curve of LN2 with the pressure decreasing from 100 kPa to 20 kPa. It can be found that, lower pressure has a significant effect on reducing the LN2 temperature. The corresponding LN2 temperature to the chosen pressure conditions of 100 kPa, 65 kPa, 45 kPa and 25 kPa are about 77.6 K, 73.7 K, 70.4 K and 65.1 K, respectively.

**FIG. 3 HERE**

Fig. 4 shows the levitation force curves vs vertical distance between HTS bulks and PMG in the case of ZFC and FC. A set of four levitation force curve loops for different pressure conditions are investigated, including 100 kPa, 65 kPa, 45 kPa and 25 kPa. As the measurement distance decreases, all curves have an approximate exponential increase and reach the maximum value at the lowest measurement position. Both in ZFC and FC, the levitation force is markedly larger in a lower operation pressure. To compare the levitation force of four pressure conditions in detail, Table I and Table II illustrate the levitation force data of the lowest position (12 mm height) in ZFC and FC, respectively. In Table I, the levitation force of four pressure conditions are 481.3 N, 535.2 N, 566.6 N and 594.5 N, respectively. Compared with the levitation force of atmospheric pressure 100 kPa, there is a 11.2% increase for the levitation force of 65 kPa. Furthermore, as the pressure continuously falls to 45 kPa and 25 kPa, the levitation force increases 17.7% and 23.5% by contrast with 100 kPa value. According to the calculation formula of levitation force [21]:

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|  | (1) |

where *m* is the magnetic moment of the HTS bulks and d*H*/d*z* is the field gradient produced by the PMG. The magnetization of the bulks is *M* = *A**J**c**r*, where the magnetization per unit volume (*V*) is defined as *m* = *MV*, *A* is a constant depending on the geometry of the bulks, *r* is the radius of a shielding current loop, and *J**c* is critical current density of the bulks. As shown in Fig. 3, with the pressure reducing , the temperature of LN2 would also decrease which could directly lead to the enhancement of critical current density inside the superconductor [22]. Consequently, under the interaction between a higher level of *J**c* and the magnetic field supplied by the PMG, the levitation force becomes more superior seen in Fig. 4.

The similar results are obtained in the case of FC, as shown in Table II. Limited by the cooling method, the levitation force in the case of FC is generally smaller than which at the same condition in the case of ZFC. However, compared with the levitation force measured under atmospheric pressure 100 kPa, the growth rate of levitation force measured under 65 kPa, 45 kPa and 25 kPa pressure condition are in accordance with that in the case of ZFC, with 11.2%, 18% and 22.1% increase. Moreover, the hysteresis loop area of curves presents a difference as well. With the pressure decreasing, the curve shows much smaller hysteresis loop which could be seen more clearly in the added inset. The hysteresis loop represents the strength of pining ability of bulks, while the superconductor could keep flux from penetrating inside and out effectively during the movement process under a low pressure condition.

**FIG. 4 HERE**

**TABLE I HERE**

**TABLE II HERE**

The measured relaxations of levitation force under four different pressure conditions were investigated as well. In order to present the ratios of levitation force decay more clearly, we implemented a normalized process for the levitation force with respect to the initial value of each pressure condition and took the natural logarithm of the time, as shown in Fig. 5. We can see that the low pressure environment could effectively restrain the relaxation decay of levitation force. As we know, the main reason causing the force decay is the flux creep inside HTS bulks. According to the classic flux creep model of Anderson and Kim [23], [24]

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| --- | --- |
|  | (2) |
|  | (3) |

where *S* is the relaxation rate, which is directly related to the factor *kT*/*U**eff*, and *U**eff* is assumed to have a logarithmic relationship with *J*, as shown in Eq. (3), *T* is the absolute temperature, *k* is the Boltzmann constant, *U*0 is the barrier height in the absence of a driving force, *U**eff* is the effective height of the pinning energy barrier to magnetic vortex motion, *J**c0* is the critical current density in the absence of thermal activation and *J* is the current density. By contrast, the higher critical current density *J**c*0 of HTS bulks under the low pressure would bring about a relatively large *U**eff*, and further causing a small relaxation rate. Consequently, the experimental results are consistent with the theoretical analysis.

**FIG. 5 HERE**

# IV. CONCLUSION

We investigated the levitation performance of HTS bulks under four different pressure conditions, including the 100 kPa (atmospheric pressure), 65 kPa, 45 kPa and 25 kPa, by a simple super-cooling platform established in-house. The temperature of LN2 corresponding to above four pressure conditions are 77.6 K, 73.7 K, 70.4 K and 65.1 K, respectively. It is found that, the levitation force has a significant promotion in the low pressure environment. And the low pressure condition is not only able to take a larger levitation force but also to reduce the hysteresis loop area of levitation curves. In addition, the low pressure environment could effective restrain the decay of levitation force as well. According to the results shown above, the low pressure condition has a significant effect on the levitation performance of HTS bulks. This study gives an efficient reference for the HTS maglev vehicle running inside the evacuated tube system, and further proves the superiority of the combination of HTS Maglev and ETT.

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Fig. 3. Measured temperature curve of the LN2 under the pressure from 100 kPa to 20 kPa.

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1. Automatically generated dates of receipt and acceptance will be placed here; authors do not produce these dates. This work was supported in part by the National Natural Science Foundation of China under Grant 51307147 and Grant 51375404, and by the State Key Laboratory of Traction Power at Southwest Jiaotong University under Grant 2015TPL\_Z02 and 2016TPL\_T01). (*Corresponding author: Zigang Deng.*)

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