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Magnetic levitation technology and its applications in exploration projects

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Abstract

An energy efficient cryogenic transfer line with magnetic suspension has been prototyped and cryogenically tested. The prototype transfer line exhibits cryogen saving potential of 30–35% in its suspension state as compared to its solid support state. Key technologies developed include novel magnetic levitation using multiple-pole high temperature superconductor (HTS) and rare earth permanent-magnet (PM) elements and a smart cryogenic actuator as the warm support structure. These technologies have vast applications in extremely low thermal leak cryogenic storage/delivery containers, superconducting magnetic bearings, smart thermal switches, etc. This paper reviews the development work and discusses future applications of established technologies.

Keywords: Magnetic levitation; High T_c superconductors; Cryostats; Space cryogenics; Superconducting bearings

1. Introduction

More and more applications [1–3] of magnetic levitation (MagLev) technology have been exploited in extensive cryogenic engineering domains. As one instance of such endeavors, AMAC International Inc.'s team of scientists and researchers has successfully applied magnetic levitation using HTS and high strength PM in an energy efficient prototype of a cryogen transfer line [4–8]. The key design issues, such as optimization of levitation unit and "smart" support structure development, are reviewed in this paper. Cryogenic test results are reported as well. The advantages of non-contact insulation through magnetic levitation support enable the associated technologies to promise low thermal loss solutions for space flight vehicles and/or planetary surface operation stations.

As an example, the magnetic levitation technology as developed by AMAC can be extended to the design of zero-boil-off (ZBO) cryotanks [3,9–11] that impose much lower cooling power demands on equipped cryocoolers. Also, the fact that cryocoolers are becoming more and more reliable makes it feasible to build flywheels consisting of passive superconducting magnetic bearings (SMBs) [1,2], i.e. bearings composed of tubular HTS and PM, that can be used in space energy storage systems. A comparison of popular magnetic bearing techniques is given in this paper to demonstrate the benefits that a passive magnetic bearing may produce.

Implementation of a transfer line with magnetic levitation units triggered the question of smart support design, which provides mechanical support when it is so warm that

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HTS–PM units are deactivated. As a consequence of such studies, a cryogenic actuator made of smart material has been prototyped and tested. Its motion is passively adjusted by temperature change in the system. No powered control units are required. No manual operations are needed either. The design principles of such a smart cryogenic actuator can be adapted for design of automatic thermal conduction switches used in cryogen storage containers, cryogenic valves, seals, and some medical applications.

2. Design of cryogenic transfer line with magnetic suspension

This Section summarizes the primary considerations on three aspects, i.e. magnetic levitation configuration, thermal, and mechanical design. While the magnetic levitation configuration optimization requires most of the time in the design process, thermal and mechanical design issues had to be analyzed and subsequently, all factors are synthesized for the purpose of improving system energy efficiency.

2.1. Magnetic levitation configuration studies

Prior to the development of the full-size prototype, which has a six-meter-long inner cryogen transferring tube, a few one-meter long transfer line prototypes were constructed to investigate candidate MagLev configurations. Three performance indices are emphasized in all MagLev configurations: (i) sagging distance, (ii) the final levitation gap, and (iii) levitation forces. Applied in this development is the field cooling (FC) levitation mechanism. This means that the HTS is initially cooled at a certain cooling height and due to the gravity of inner line and cryogen, the HTS will approach the PM to accumulate enough levitation force to balance the loads. In a compact MagLev transfer line design, 2–3 mm travel is allowable and larger sagging of the inner line may compress the superinsulation and cause solid contacts between inner and outer vessels at some regions. The final levitation gap also determines the size of the transfer line and gap between the superinsulation and the inner wall of the outer pipe. Levitation forces (sometimes in terms of stiffness) are analyzed and measured frequently to evaluate the load capacity of certain levitation units in view of both lifting and stabilization requirements.

Inspired by the cylindrical shape of conventional cryogenic transfer lines, HTS tubes and PM rings are firstly concentrically assembled to form the MagLev units. Multi-seeded polycrystalline melt-textured YBCO tubes are specially designed and fabricated for experimental verifications. It is found that fabrication of PM rings with ideal radial magnetization is quite costly. Therefore, a "sandwiched" magnetic design that uses PM rings separated by iron shims is adopted to create the uniform radial magnetic field. Fig. 1 illustrates such a sandwich design. High grade, e.g. N45 and N50, rare earth NdFeB rings are used in the test. To obtain strong magnetic excitation, the field intensities of various PM and iron combinations are analyzed using finite element codes. From the magnetic field analysis results, it is observed that increasing the PM axial length results in higher flux density (as expected), whereas thicker iron shims decrease the flux density. It is also found that if the total length of the PM subassembly is limited in considerations of assembly weight and cost, the most powerful and economical magnetic design is given by the PM–Fe–PM design as shown in Fig. 1(a). Thereafter, levitation forces generated by MagLev units consisting of YBCO tubes and a few example PM–Fe–PM combinations are measured for comparison. The results are shown in Fig. 2. PM rings of dimensions OD = 75 mm, ID = 55 mm, and length = 10 mm are clamped together with one iron shim of various thickness = 2, 3, and 4 mm. The conclusion is that iron ring thickness of 3 mm gives the largest levitation force, approximately 20 N, at a displacement of 2 mm. However, the estimated load capacity requirement in a full-scale transfer line is >40 N per support unit.

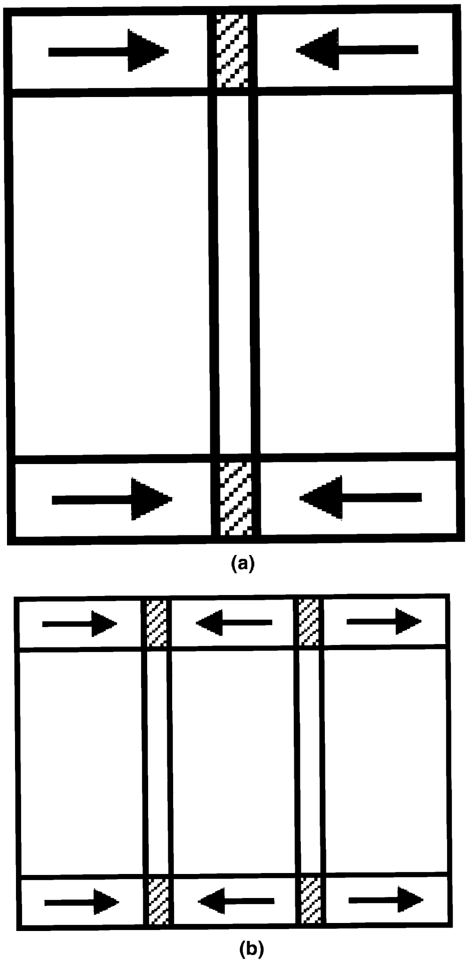

Fig. 1. Sandwiched PM rings and iron shims magnetic design: arrows denote the polarization of PM rings: (a) PM–Fe–PM, (b) PM–Fe–PM–Fe–PM.