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 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,

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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 HFS 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 tings 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 2mm. However, the estimated load capacity requirement in a full-scale transfer line is >40 N per support unit.

Another levitation design notion, the multiple-pole levitation system, as illustrated in Fig. 3, was then investigated for enhancement of levitation force. This design suggests supporting the inner tube by use of a few discrete HTS—PM blocks. Shown in Fig. 3 is a concept using four poles to form the support system. In fact, variations from this concept are also adaptable to a real transfer line support design, depending on the pipeline orientation and possible assembling requirements. The multiple-pole design also allows for the freedom of altering the shapes and structures of the HTS and PM, respectively. For example, HTS can be tiles with curvature or simply rectangular blocks. The former facilitates wrapping of superinsulation and the latter is more economical.

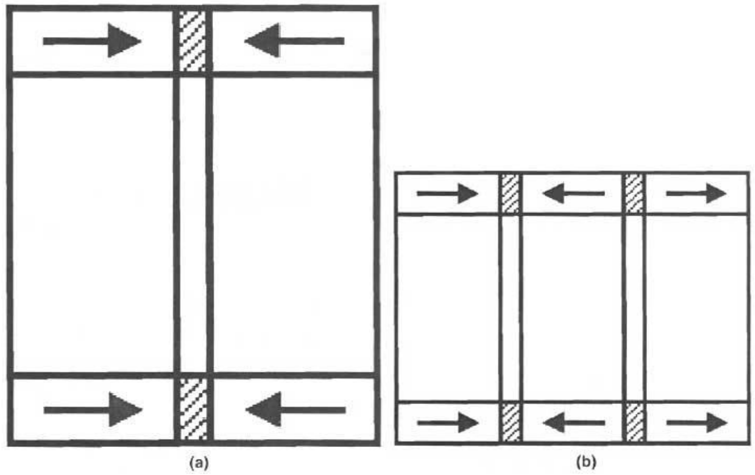

Fig. 1. Sandwiched PM rings and iron shims magnetic design: arrows denote the polarization of PM rings: (a)PM-Fe-PM, (b)PM-Fe-PM-Fe-PM.

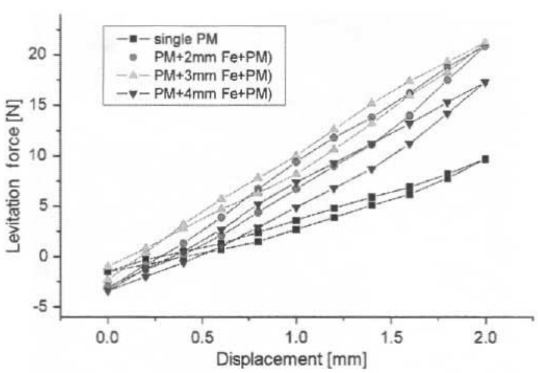

Fig.2. Measured levitation forces for tubular MagLev units with varied magnetic excitations

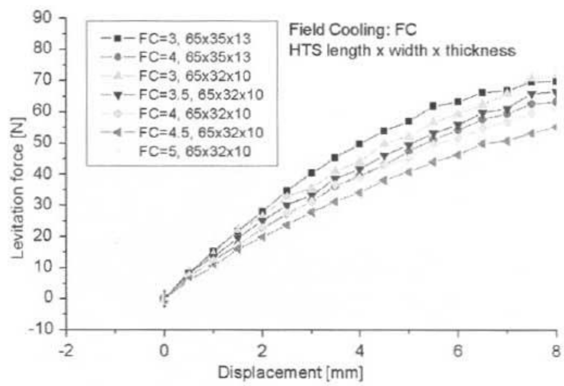

Fig.4. Single pole levitation force measurement results.

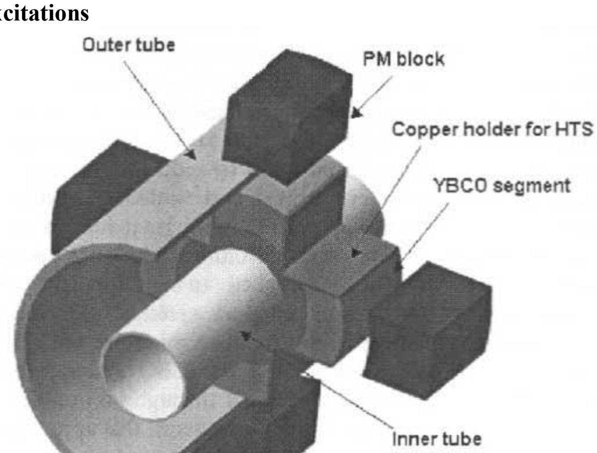

Fig.3. Multiple-pole magnetic levitation design.

Based on intensive experimental studies, it is concluded that for providing unidirectional support force and axial stabilization, a two-pole MagLev unit can be used. Fig. 4 shows the measured levitation forces for one out of the two poles that are used in the full-scale transfer line prototype. A number of levitation force curves are obtained experimentally to investigate the effect of YBCO segment sizes, e.g. length 65 mm, width 35 mm, and thickness 13 mm, and thickness 13mm, and FC position on levitation performance. Note that a special magnetic design of the PM has been undertaken, it is seen that with one pole, at a displacement of 2-3 mm, levitation force of 20-40 N can be achieved easily. This means with the two-pole MagLev unit, the required 40 N support force can be reached with <2 mm sagging of the inner line. This is proved in the levitation tests that will be discussed later.

2.2. Thermal and mechanical design

In a MagLev transfer line, thermal conduction is eliminated because of the non-contact support provided by MagLev units. High vacuum ensures the convection heat leak to be minimal. The radiation between warm outer vessel and cold inner tube is largely reduced by wrapping of 20-30 layers of multi-layer-insulation (MLI). In the full- scale prototype, an initial minimum clearance of approximately 7 mm is maintained in between the outmost MLI layer and inner wall of outer vessel. This is to assure that when the inner line sags for 1-2 mm, MLI will not touch the outer vessel and form a thermal conduction path.

The inner tube is made of stainless steel and has a 6-m length. When the temperature drops from room temperature of approximately 300 K to cryogenic temperature, e.g. 77 K for liquid nitrogen, the inner tube will contract. Two bellows are hence mounted at the ends of the inner tube to cancel the thermal stress due to contraction. Totally, three MagLev supports are used. To evenly distribute the mechanical loads, the three supports are positioned at 1.0, 3.0, and 5.0 m, respectively, According to a rough calculation, at the two side MagLev supports, there will be approximately 6 mm axial movement during system cooling down. The deviation is accommodated by displacing the centerline of YBCO block 6 mm axially.

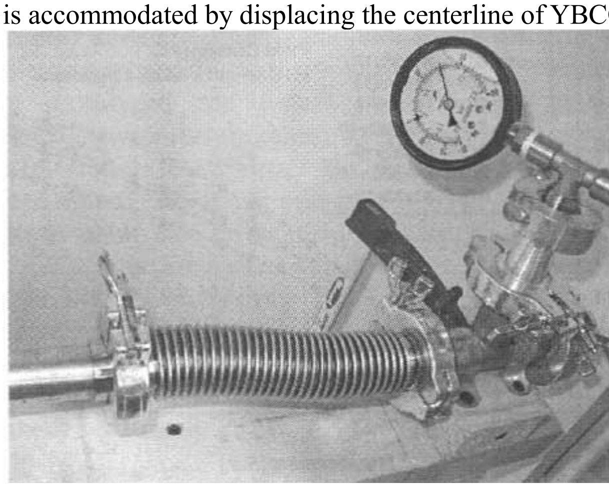

Fig. 5. Squirming of bellows under pressure at the end of an unstrained tube.

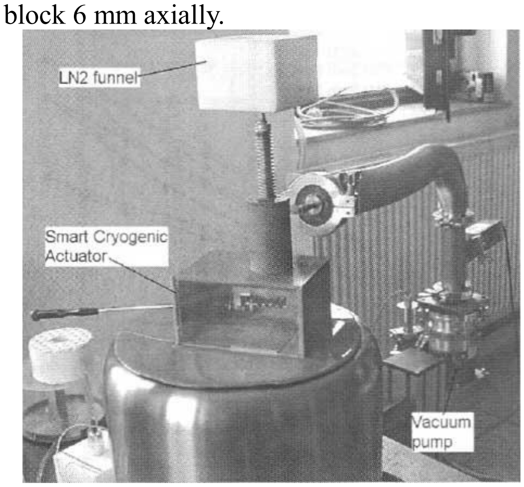

Fig.6. AMAC's smart cryogenic actuator in test.

The flexible bellows trigger a mechanical instability of squirming. This happens due to the one atmosphere air pressure differential between interior of inner tube and its vacuum jacket. Fig. 5 is a visualization of such squirming phenomenon by over-pressurizing a water-filled stainless steel tube and bellows. The force needed to balance the squirming is also measured in such squirming test in air environment. Approximately 5.0N additional support force is needed to keep the inner line free of squirming, which may result in thermal contacts between the bellows and the warm outer wall.

3. SMART CRYOGENIC ACTUATOR DEVELOPMENT

A warm support structure is required in such a MagLev transfer line to keep the inner line supported at warm condition when the HTS-PM levitation units are deactivated. This is preferably to be done in a passive way that does not require power supply, control electronics, etc. AMAC has prototyped a smart cryogenic actuator (Fig. 6) to function as a warm support structure in the MagLev cryogenic transfer line. The actuator is attached to the cold inner line so that it is passively controlled by the variation of temperature during cooling down or warming up. The actuator is able to move its working arm over a 6 mm distance and carry up to 60 N weight per support. The disengage/engage characteristic of such actuator has extensive applications in space cryogenics and industry.

4. MAGLEV TRANSFER LINE PROTOTYPE AND CRYOGENIC TESTS

The full-scale prototype MagLev transfer line (Fig. 7a) was constructed with three manually operated warm supports installed. These warm supports are basically stainless steel rods, when switched on, they will introduce thermal conduction as a conventional transfer line does. The smart cryogenic actuator is planned to equip the MagLev transfer line during commercialization stage. Comprehensive cryogenic test results of the MagLev transfer line are presented in other publications [6,8]. Below is a summary of the key findings from all tests:

- Observed from inspection mirrors, the maximum sagging distance at three supports ranges from 0.5 to 1.0 mm. The levitation is very stable and repeatable.
- Comparing cryogen boil-off rates (Fig. 7b) monitored by a flowmeter at the warm support on and off conditions,approximately 30% saving on boil-off amount is achievable by use of magnetic levitation.

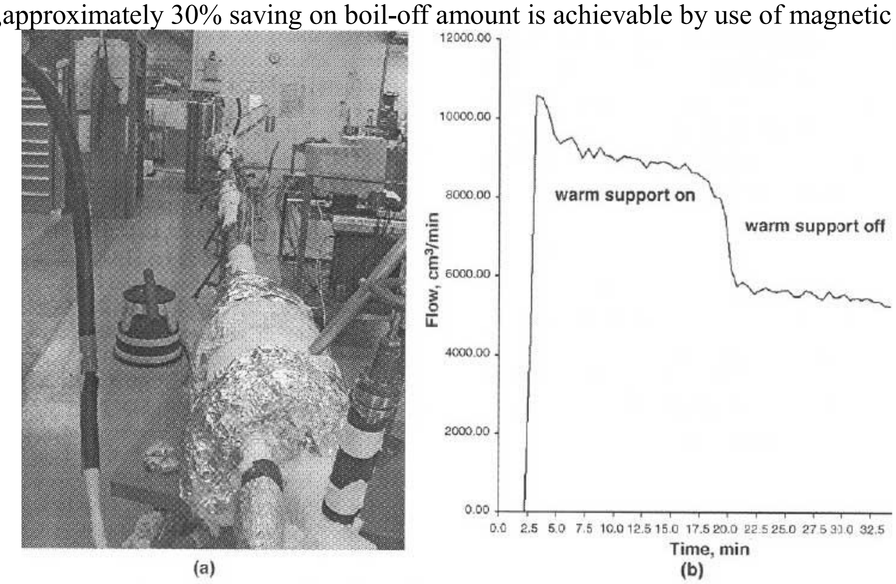

Fig.7. The MagLev transfer line prototype and its thermal performance(a)prototype in tests,(b)cryogen boil-off rate.

5. POTENTIAL MAGLEV APPLICATIONS

5.1. Low thermal leak space cryostats

NASA is planning a number of future missions that will use cryogenics. These include missions with cooled scientific instruments and missions using cryogenic propellants. Minimizing the thermal load on the cryogenic parts of the flight system will reduce the launch mass of the cooling system (cryocooler, power supply, and heat rejection) or minimize the size of the cryogen tanks by reducing the rate at which the cryogen is evaporated and vented overboard. One of the significant sources of the thermal load is the support system. The magnetic levitation techniques developed by AMAC can be applied to development of advanced non-contact tank support systems. For long duration space flight, it is important to minimize the heat leak into a cryogen tank. For a non-ZBO system, this approach minimizes the cryogen lost through boil off during the life of the mission. For ZBO systems, this approach minimizes the mass of the cooling system (cryocooler, power source, and heat rejection subsystems). In either case, the total system mass is minimized; reducing launch costs and/or permitting increased payloads.

5.2. Superconducting magnetic bearings

Three types of bearings are used in engineering structures: mechanical bearing, active (electro-) magnetic bearing (AMB), and superconducting magnetic bearing. The mechanical bearings have already been standardized in design and supplies. A mechanical bearing needs lubrication and the friction energy loss increases as speed and load does. Magnetic bearings offer a "frictionless" solution with levitated shafts that can spin at really high speeds. An AMB needs electronic control and power supply. Development of AMB inevitably involves considerable effort on the associated control units design and verifications. Development of a SMB is comparably less costly. With an HTS stator, the coolant can be liquid nitrogen, which is cheap to procure.

The magnetic levitation technologies developed in this project can be applied to the development of high performance SMBs in the future. Besides its potential application in industry structures, such as turbomachineries, SMBs are broadly used in flywheel energy storage systems (FESS). NASA has continuously pursued the research and development in high energy FESS through multiple projects, all of which demand advanced magnetic bearing technology. As one of the key components of a FESS, bearing performance and capability significantly affect the integral system efficiency and the energy that can be stored. With current AMB technology developed at NASA Glenn Research Center, an AMB flywheel is able to spin at a maximum speed of 55,000-60,000 rpm for Low Earth Orbit applications. The use of extremely low-loss high-temperature superconducting (HTS) bearings is necessary to meet the long idle time requirements of future Lunar and Martian missions. High specific energy and high energy storage are demanded, so that rotational speeds of perhaps 150,000-200,000 rpm, will be needed.

5.3. Smart thermal switch

Application of the passively smart thermal switch can be used for thermal isolation of de-powered cryocoolers. It can significantly enhance the thermal efficiency of liquid hydrogen, helium, and O_2 and CH_4 storage tank and reduce its size and required cooling power. Cryogen storage vessels with very high thermal performance and high volume efficiency are strongly demanded by spacecrafts expecting long duration missions. These techniques will result in ZBO tanks with significantly smaller cryocoolers. Tanks are also needed whenever cooling of instruments (gyroscopes, flywheels, and telescopes) is required.

These technologies in terrestrial and space applications opens the possibility for reduced heat leakage and longer storage of cryogen, thus offering the potential of extending many missions or reducing the launch mass to accomplish a given mission. It also can be widely used in extensive commercial applications include: (1) for liquid hydrogen, helium, nitrogen storage in transportation industry in the future, (2) LH_2 powered cars, buses, planes and rockets (smaller rockets such as envisioned for on-orbit payload transfer operations or interplanetary propulsion) (3) long time storage.

6. CONCLUSIONS

A prototype energy efficient cryogenic transfer line with magnetic suspension supports has been developed. Cryogenic tests showed that stably and repeatable levitations are achieved in the prototype. The prototype also demonstrated a nearly 30% saving on cryogen boil-off rate. An optimized design, without special test equipment, intermediate flange joints, and view ports, is anticipated to have higher saving on the boil-off rate. The key technologies developed, including the special magnetic levitation design and smart cryogenic actuator, will have applications in low thermal leak cryotanks or other cryostats, superconducting magnetic bearings for machineries or FESS, and smart, passively controlled, decoupling thermal switches, valves, seals in cryogenic research industry as well.

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REFERENCES

[1] Moon FC, Chang PZ. Superconducting levitation: applications to bearings and magnetic transportation. New York: Wiley: 1994.
[2] Hull JR. Superconducting bearings. Supercond Sci Technol 2000;13:R1-15.
[3] Walter H, Arsac S, Bock J, Siems SO, Cnaders W-R. Leenders A, et al. Liquid hydrogen tank with cylindrical superconducting bearing for automotive application. IEEE Trans Appl Supercond 2003;13:2150-2
[4] Shu QS, Cheng G, Yu K, Hull JR, Demko JA, Britcher CP, et al. Energy efficient cryogenic transfer line with magnetic suspension. Hydrogen in Materials and Vacuum Systems: First International Workshop on Hydrogen in Materials and Vacuum Systems. AIP Conference Proceedings 2003;671:321-7.
[5] Shu QS, Cheng G, Yu K, Hull JR, Demko JA, Britcher CP, et al. Low thermal loss cryogenic transfer line with magnetic suspension. Adv Cryog Eng 2003;49B:1869-76.
[6] Shu QS, Cheng G, Susta JT, Li D, Hull JR, Demko JA, et al. A six-m long prototype of the magnetic levitation

suspended cryogen transfer line. IEEE Trans Appl Supercond 2005;15(2):2297-300.
[7] Shu QS, Cheng G, Susta JT, Hull JR, Demko JA, Britcher CP, et al. Development of an energy efficient cryogenic transfer line with magnetic suspension. Presented at the Cryogenic Engineering Conference 2005, Keynote, CO, August 29-September 2.
[8] Fesmire JE, Augustynowicz SD, Nagy ZF, Sojourner SJ, Shu QS,Cheng G, et al. Testing of prototype magnetic suspension cryogenic transfer line. Presented at the Cryogenic Engineering Conference 2005, Keynote, CO, August 29-Septemher 2.
[9] Baker R, Guernsey C, Kittel P, Plachta DW. Cryogenic propulsion with zero boil-off storage applied to planetary exploration. Presented at 2005 AIAA Joint Propulsion Conference. Tucson, AZ.
[10] Plachta DW, Christie RJ, Jurns JM, Kittel P. Passive ZBO storage or liquid hydrogen and liquid oxygen applied to space science mission concepts. Presented at 2005 Space Cryogenics Workshop, Colorado Springs, CO.
[11] Plachta DW, Christie RJ, Jurns JM, Kittel P. ZBO cryogenic propellant storage applied to a Mars sample return mission concept. Presented at 2005 Cryogenics Engineering Conference Keystone,CO.