9 Magnetism in clean energy and environment

Kelvin T. H. Hui, L. F. Cheung, K. S. Lui, Philip W. T. Pong
Department of Electrical and Electronic Engineering, The University of Hong Kong

9.1 Introduction

Implementation of modern clean energy technology was crippled by its inefficiency, yet magnetism might be the answer to the problem. First, power generation involving turbines and energy storage systems infused with flywheel technology has many limitations, namely frictional loss, speed limit, etc. By introducing superconductor bearings, it is possible to dramatically reduce frictional loss by magnetic levitation. Second, coolants used in traditional refrigeration has been causing extensive environmental problem. Such problem can be solved by using magnetic refrigeration which does not require traditional coolants at all. Third, magnetism may also be the key to overcome technical barriers in nuclear fusion. The difficulty of harnessing fusion power is to provide a stable and extremely hot environment for fusion to take place. This can be achieved by magnetic levitation and confinement. This chapter will provide a complete walkthrough on how all these solutions are possible.

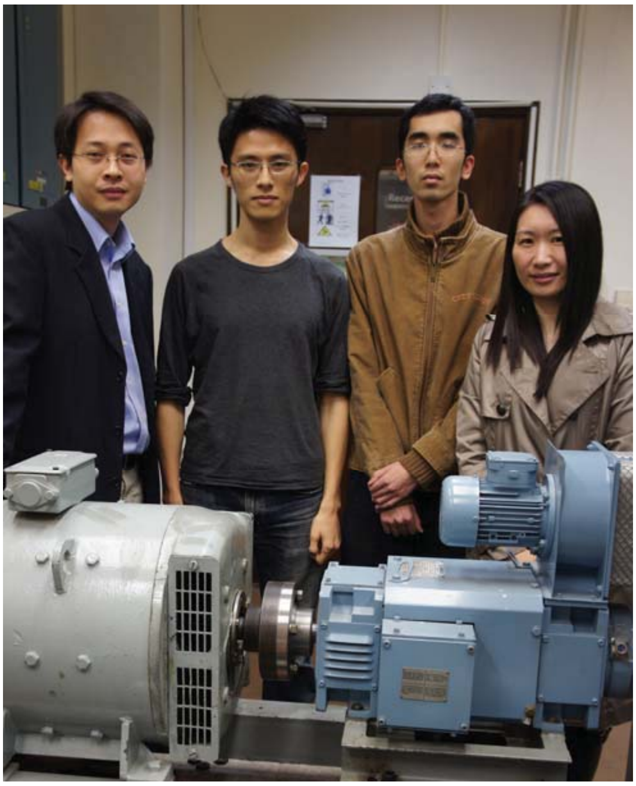

Figure 9-1 Philip W. T. Pong, Kelvin T. H. Hui, L. F. Cheung, K. S. Lui and an electrical machine

9.2 Magnetism in clean energy generation – a case study wind energy

9.2.1 Structure of wind Turbine

Wind turbines (Figure 9-2) are commonly used in clean energy. A wind turbine consists of three components, namely support, rotor, and generator. Support components provide mechanical support for wind turbines. The rotor components consist of rotors and blades that are responsible for converting wind energy to rotational energy. The generator components consisting of an electrical generator and a gearbox are responsible for converting rotational energy to electrical energy. Wind turbines are clean because they do not produce any carbon pollutants during the energy generation process.

Figure 9-2 Wind turbines

9.2.2 Energy storage system: flywheel

Since wind speeds are not constant, flywheel systems are often used to store the wind energy. A flywheel system (Figure 9-3) functions by accelerating the rotor to a high speed to store the energy as rotational energy. By conservation of energy, energy can be later extracted from the system by converting rotational energy back into electrical energy. It has several advantages over other energy storage systems. First, it is easy to store energy comparing to chemical batteries. Second, it has a relatively long life-time [1]. Lastly, it does not impose any environmental disposal problems such as chemical wastes as in chemical batteries.

Figure 9-3 Flywheel system

9.2.3 Frictional loss and limitation of existing bearing system

In conventional rotor systems, bearings are in contact with the rotor shafts. In other words, there is always friction between the contact surfaces. This limits the rotational speed of turbines and flywheels. If the rotational speed exceeds the speed limit of bearings, it will cause significant energy loss and damage to the mechanical components. A better alternative is to use magnetic bearings.

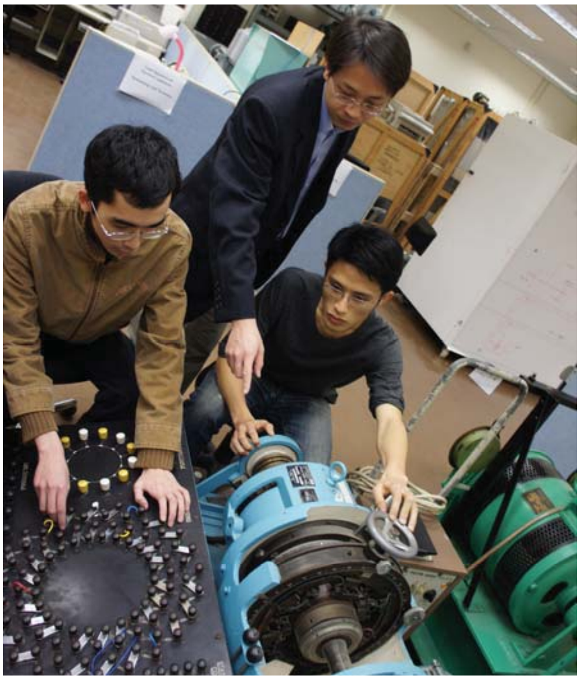

Figure 9-4 Energy efficiency of electrical machines can be improved by magnetism

9.2.4 Magnetic bearing

Mechanism of magnetic bearings

Traditional bearings (Figure 9-5) suffer the friction at the mechanical contact between two surfaces. Magnetic bearings can alleviate this problem, and they support the load by magnetic levitation. They make use of mutual magnetic repulsion between the bearings and loads to establish levitation of the loads. This greatly reduces the mechanical contact between two surfaces and thus minimizes the friction. This increases the speed limit and extends the service lifetime of the bearings.

Figure 9-5 The performance of traditional bearings is constrained by friction

Limitations of magnetic bearings

However, there are some drawbacks on magnetic bearings. Magnetic bearings need sensors, amplifiers, and controllers to control magnetic field strength to regulate the system. This increases the cost and the complexity of the system design. On the other hand, compared to normal bearings with the same load, magnetic bearings are larger and more difficult to install.

9.2.5 Superconductor bearings

How it works

Superconductors give perfect diamagnetic effect which can produce effective magnetic levitation. Diamagnetic effect refers to the phenomenon where an opposite magnetic field is induced in a material by an externally applied magnetic field. In Figure 9-6, we can see that there are no field lines penetrating through the superconductor. Instead, the field lines are diverted around the superconductor. Therefore, the superconductor bearings do not require external power supply and the bearings are suspended passively because the suspension is not caused by mutual repulsion.

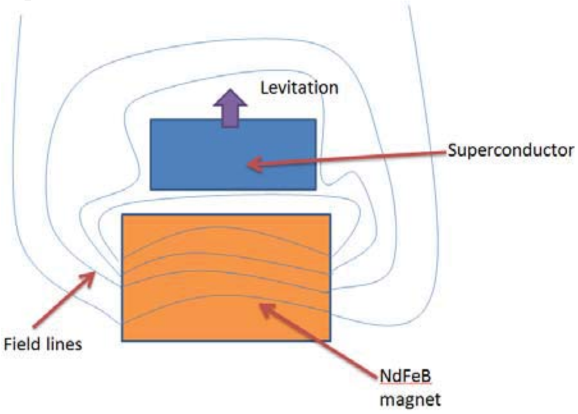

Figure 9-6 Behavior of a superconductor under the influence of magnetic field.

Advantages over magnetic bearing systems

The passive magnetic levitation does not rely on any control systems. Size and complexity of the bearing systems can then be greatly reduced. Unlike coil driven magnetic bearings, it does not need energy to sustain suspension. Thus it is comparatively more energy efficient than magnetic bearing systems.

Obstacles and vision

However, superconducting bearings must operate at a very low temperature (below around 100 K) to achieve superconductivity. This is a big technical barrier to overcome for practical applications. The low-temperature environment can be created by using liquid nitrogen or liquid helium. This has been applied to small-scale superconductor flywheel systems but not large-scale clean energy generators like wind turbines. Apart from cooling methods, researchers are looking for superconductors which can operate at higher temperatures.

9.3 Magnetism in fusion power

Fusion power is regarded as clean energy because it does not produce carbon emission or radioactive by-products. Deuterium, a stable hydrogen isotope with a natural abundance in ocean, is commonly used as fuel source in nuclear fusion. In fusion, two atomic nuclei are combined into a heavier nucleus. The combination of two nuclei will release heat that can be used to generate electricity.

9.3.1 Current problem in nuclear fusion

In order to make two positively charged light atomic nuclei fuse together, we can make use of the ionization of plasma. In plasma state, charged particles, positive ions, and negative electrons inside an atom will be dissociated. This can help nuclear fusion to ignite. However, a stable and very high-temperature environment with high-density plasma (~100 million degree Celsius) has to be sustained. Levitated dipole experiment (LDX) is therefore carried out to overcome this technical challenge.

9.3.2 Levitated dipole experiment (LDX)

Levitated dipole experiment can provide a solution by applying magnetic suspension and confinement. The levitating dipole reactor used in the experiment consists of a giant torus-shaped magnet suspended by electromagnetic field [2]. This provides effective separation of heat transfer. Moreover, the LDX takes a new approach of magnetic confinement. Magnetic field is used to confine the hot plasma such that the plasma condenses inside the magnet (turbulent pinching) instead of spreading out [3][4]. As such, high-density plasma can be obtained which is critical for starting the fusion.

9.4 Magnetism in refrigerating technology

9.4.1 Current problem in refrigeration

Common household refrigerating systems in air-conditioning and refrigerators use vapor-compression as a refrigerating mechanism. The vapor-compression uses coolants as a medium which are used to removes heat in the refrigerating systems. Therefore, coolants are required. Chlorofluorocarbons (CFCs) were widely used as coolants but they are now banned because their leakages to the atmosphere are causing ozone depletion. CFCs perform catalytic free-radical reactions [5] in the ozone layer which is a layer filtering most of the UV light from the sun. In the presence of UV light, CFCs produce chlorine radicals and react with ozone to form reactive ClO^- (hypochlorite or Chlorate (I)) compounds. This causes continuous loss of ozone layer and creates ozone holes in which UV light can reach the Earth surface directly without natural filtering [6]. The existence of ozone holes increases the potential hazard of skin cancers [7] and cortical cataracts [8]. Most of the refrigerators nowadays use alternative coolants like hydrofluorocarbons (HFCs) which are less reactive than CFCs. However, HFCs are flammable and extra monitoring costs are needed for refrigeration [9].

9.4.2 *Magnetic refrigeration*

Magnetic refrigerating system can be one of the clean alternatives. Magnetic refrigeration is based on the principle of the magnetocaloric effect (MCE) which does not require any traditional coolants or flammable materials. The magnetocaloric effect was discovered in iron sample by Warburg and its sophisticated mechanism was later explained by Debye and Giauque independently [10]. Currently, MCE is not applicable in domestic use yet. One of the reasons is because large MCE can only be achieved by pumping helium vapors below 0.3 K. Fortunately, the discovery of giant MCE in some alloys like gadolinium alloy $Gd_sSi_2Ge_2$ in 1997 by Pecharsky and Gschneidner makes MCE an emerging technology in magnetic refrigeration. [10][11][12].

9.4.3 Mechanism of magnetic refrigeration

The mechanism of magnetic refrigeration is illustrated in Figure 9-7. First, the magnetic dipoles inside the MCE material are disoriented. After magnetization, the magnetic dipoles become orientated and the disorderliness of the material reduces. According to thermodynamics, the reorientation decreases disorderliness resulting in decreases in entropy and heat capacity. In other words, the material releases heat and becomes cooled. After that, the material undergoes demagnetization. This causes disorientation of the magnetic dipoles gand increases disorderliness of the dipoles. The material then absorbs heat from surrounding. This reduces the surrounding temperature and causes refrigerating effect. This cycle is repeated to sustain the refrigerating function.

9.4.4 Advantages over current vapor-compression refrigeration system

Based on the above mechanism, the cooling effect comes from the entropy change of the MCE materials. Hence magnetic refrigeration does not need any traditional coolants. On the other hand, with some advanced MCE materials such as praseodymium-nickel alloys, it can create an extremely low temperature environment. Previously, it enabled scientists to approach within one thousandth of a degree of absolute zero [13]. Its excellent cooling effect will also aid the operation of superconducting bearings mentioned earlier. Therefore, it can promote cleaner operation for modern refrigerating systems without the risk of damaging ozone-layer.

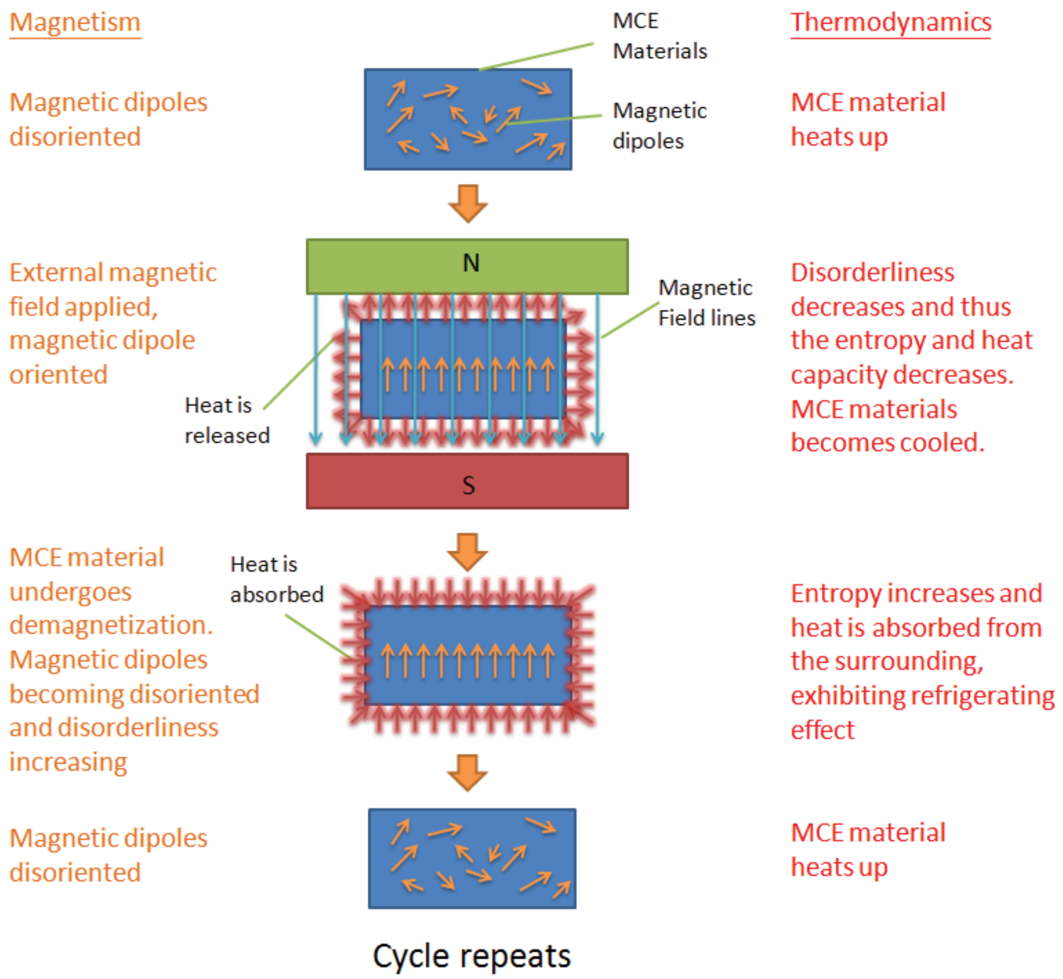

Figure 9-7 Schematics showing the mechanism of magnetic refrigeration

9.4.5 *Obstacles and vision*

Magnetic refrigeration is still at the stage of development because current MCE materials have a lot of constraints. One of them is the hysteresis loss under sweeping magnetic field. New materials for magnetic refrigerating systems are needed. One of the possible materials is lanthanum-iron-silicon alloy $La(Fe,Si)_{13}$ [14]. $La(Fe,Si)_{13}$ is an alloy which exhibits significant reduction of thermal and field hysteresis. Therefore, the use of $La(Fe,Si)_{13}$ can shorten preparation time and decrease cost in magnetic refrigeration.

9.5 Outlook

Engineers and scientists' continuous efforts have made enormous progress in clean energy research and development based on magnetism. Nevertheless, there are still many technical barriers.

First, operating temperatures of current superconductors are still too low. This makes applying superconducting bearings in wind turbines and flywheel systems difficult. Keeping the bearings at low temperature requires a strong cooling unit which consumes a lot of energy. The recent research in high-temperature superconductors may provide a feasible solution, yet more effort is needed to develop a room-temperature superconductor for clean energy generation. Magnetic refrigeration has many merits, yet it suffers from low efficiency because of serious hysteresis loss in current MCE materials. Better MCE materials have to be developed to decrease the hysteresis loss and improve their performance. In fusion power, a stable and extremely high-temperature environment with high-density plasma can be produced by using levitating dipole technology. This research is still in its infancy and hopefully it can become practical in the near future.

Clean energy and environment is the most important issue for the 21st century. Through continuous research and cooperative efforts, magnetism will surely take an important role in assisting the large-scale deployment and utilization of clean technologies and providing a cleaner environment for generations to come.

Reference

[1] D.G. Christopher and R. Beach, "Flywheel technology development program for aerospace applications," *Aerospace and Electronics Conference, 1997. NAECON 1997*, vol. 2, pp. 602-608, 1997.

[2] D.L. Chandler, "Levitating magnet brings space physics to fusion," 2010. [Online] Available: http://web.mit.edu/newsoffice/2010/fusion-ldx-0125.html

[3] A. Iiyoshi and K. Yamazaki, "The next large helical devices," *Physics of Plasmas,* vol. 2, no. 6, 1995.

[4] A. C Boxer, R. Bergmann, J. L. Ellsworth, D. T. Garnier, J. Kesner, M. E. Mauel,

P.Woskov, "Turbulent inward pinch of plasma confined by a levitated dipole magnet," *nature physics*, vol. 6, pp. 207-212, 2010.

[5] M.J. Prather, R.T. Watson, "Stratospheric ozone depletion and future levels of atmospheric chlorine and bromine," *Nature*, vol. 344, pp.729-734, 1990.

[6] L.T. Gidel, P.J. Crutzen, and J. Fishman, "A Two-Dimensional Photochemical Model of the Atmosphere 1: Chlorocarbon Emissions and Their Effect on Stratospheric Ozone,"*Journal of Geophysical Research*, vol. 88, pp. 6622-6640, 1983.

[7] H. Slaper, G.J.M. Velders, J.S. Daniel, F.R. de Grujl and J.C.V. der leun, "Estimates of ozone depletion and skin cancer incidence to examine the Vienna Convention achievements," *Nature*, vol. 384, pp. 256-258, 1996.

[8] S.K. West, D.D. Duncan, B. Muñoz, G.S. Rubin, L.P. Fried, K. Bandeen-Roche, O.D. Schein, "Sunlight Exposure and Risk of Lens Opacities in a Population-Based Study," *The Journal of American Medical Association*, vol. 280, no. 8, pp. 714-718, 1998.

[9] J.M. Calm, D.J. Wuebbles, and A.K. Jain, "Impacts on global ozone and climate from use and emission of 2,2-dichloro-1,1,1-trifluroethane (HCFC-123)," *Climate Change*, vol. 42, pp. 439-474, 1999.

[10] B. Podmiljšak, "The magnetocaloric effect," *Jožef Stefan International Postgraduate School. Seminar for the lecture "Physics of materials"* [Online] Available: www.ijs.si/~kutnjak/reprints/Magnetocaloric.pdf

[11] A.M. Tishin and Y.I. Spichkin, *The magnetocaloric effect and its applications.* Bristol and Philadelphia: Inst. Phys. Publ, Institute of Physics Publishing, 2003.

[12] F.C. Fernandez, PhD Thesis, *Magnetocaloric effect in Gd5(SixGe1-x)4 alloys*, vol. 66, 2001.

[13] J. Emsley, *Nature's Building Blocks*, Oxford University Press, p. 342, 2001.

[14] J. Lyubina, O. Gutfleisch, M.D. Kuz'min, M. Richter, "La(Fe,Si)13-based magnetic refrigerants obtained by novel processing routes," Journal of Magnetism and Magnetic Materials, vol. 321, no. 21, pp. 3571-3577, 2009.