CHALLENGES AND OPPORTUNITIES FOR INTRODUCING MAGNETIC COOLING TECHNOLOGY TO MARKET

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Abstract

The global refrigeration and cooling industry is truly enormous; the International Institute of Refrigeration (IIR) estimated in 2015 that 3 billion refrigeration, air-conditioning and heat pump systems are in operation worldwide consuming 17% of the overall electricity globally used, and that the refrigeration sector is worth 300 billion USD of global annual sales and employs about 12 million people worldwide[1].The industry is essential for ensuring high-quality and safe food for billions of people, it keeps the internet running, and provides ultimately office, home and car comfort; many vitally important medical, chemical and industrial processes rely on it. In short it is one of the critical technologies of the modern world. The aim the presentation is to discuss the challenges that magnetic cooling developers encounter in their attempt to introduce their solutions to market as a well as the possible market drivers towards the adoption of magnetic refrigeration technology.

Introduction

Radical Innovation is generally a complex process, rather than a discrete event. It is often pioneered by smaller firms, or new market entrants, and generally implies a difficult, lengthy and risky process. System-wide adoption and diffusion of radical innovations nearly always depends on incremental improvements, refinements and modifications, the development of complementary technologies and organizational change and social learning"[2]. In this regard magnetic refrigeration has the potential, as a technology, to be a radical new technology. Recent organizational literature shows that the acceptance and market uptake of radical new technologies requires the endorsement of different social audiences that are defined as "agents with an interest in a domain and control over material and symbolic resources that affect the success and failure of the claimants in the domain."[3] The notion of a social audience is akin to the concept of social groups developed by Pinch and Bijker[4] namely key constituencies that shape the adoption of new technologies, ideas or artefacts in a given market space. The audience's behaviour has a huge influence on the market success of a radical new technology, in particular when this technology is meant to disrupting an existing one[5]. Also, some audiences have stronger influence than others on the development and adoption of new technologies. As far as the magnetic refrigeration technology is concerned different audiences can be identified:

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[1] IIR 29th Informatory Note on Refrigeration Technologies 02/12/2015. Also available from http://www.iifiir.org/userfiles/file/publications/notes/NoteTech_29_EN_kf8kw7bg.pdf (last access 07/12/2016.)
[2] OECD Science, Technology and Industry Outlook 2012. Available at http://www.oecd-ilibrary.org/science-and-technology/oecd-science-technology-and-industry-outlook-2012_sti_outlook-2012-en (last access on Nov. 21st 2016.)
[3] Hsu, G., M. Hannan, Identities, Genres, and Organizational Forms, Organization Science 16(5), pp. 474-490, 2005.
[4] Pinch, T. J., Bijker, W. E., The Social Construction of Facts and Artefacts: Or How the Sociology of Science and the Sociology of Technology Might Benefit Each Other. In Bijker, W. E., Hughes, T. P., Pinch, T. J. (Eds.), The Social Construction of Technological Systems: New Directions in the Sociology and History of Technology (pp. 17 – 50). Cambridge, Massachusetts: The MIT Press, 1989.
[5] Cattani, G., Ferriani, S., Lanza, A., Navigating the Sea of Controversy: The Legitimation Journey of John Harrison's Marine Chronometer, Working Paper of the Stern School of Business, New York University, 2012.

- The market regulator such as governments or equivalent.
- End users: both consumers and businesses.
- The industry and the finance world, which have a vested interest in the technology to be disrupted -in this case the gas compression technology- such as, for example, the refrigerant gas manufacturers or the gas compressor manufacturers or do not have yet a vested interest, such as the electric motor manufacturers.
- Other social groups that influence directly governmental or commercial policies and public opinion, such as ONGs, industry lobby groups and media.

The role of government

An increasing number of governments have approved legislative measures that aim to encourage the adoption of more efficient and environmentally friendly technologies, both by outlawing the least efficient products and by forcing manufacturers to inform consumers about the efficiency of their solutions. The governments' support of R&D activities across a range of technologies that may eventually help their policy objectives revealed to be very positive[6]. For example, in Europe there are national programmes and the European Commission's Framework Programme for Research and Development; in the US the Department of Energy provides extensive grant funding opportunities; in the Japan there are R&D funding schemes provided by NEDO (New Energy and Industrial Development Technology Organisation.) All these programmes provided funds to magnetic cooling at room temperature research activities. It is worth mentioning that in a technology review by the US Department of Energy, magnetic refrigeration is seen as a practical near-term technology that has the potential to displace the gas compressor[7].

The role of end users

The second audience is represented by end users, who are either consumers or business users. Micro-economic studies have extensively considered both the enabling factors and the barriers for customers to buy and adopt more efficient appliances[8]. In some regions such as Western Europe consumers are increasingly willing to pay a premium price for high efficiency appliances. For example, in 10 European countries from the year 2000 to the year 2013 every high efficiency fridge introduced in the market and labelled with added + to the letter A, became the best selling product in the 7 to 8 years following their launch, despite having a higher initial price.
Business users such as fast food chains and supermarkets started to buy and to publicise the adoption of more environmentally friendly cooling solutions, with the aim of increasing their environmental credentials. Ultimately this trend could continue if results of a return over investment analysis (which normally includes the maintenance costs over the product life time and the level of technical support needed by the technology) are positive.

[6] Correa, P., Andrés, L., and Borja-Vega, C., The Impact of Government Support on Firm R&D Investments - A Meta-Analysis, The World Bank Entrepreneurship and Innovation Unit, South Asia Sustainable Development Department Water and Sanitation Program, July 2013.
7 DOE: National Lab. report: PNNL-19259, page 5
[8] Ryan, L., Moarif, S., Levina, E., Baron, R., Energy Efficiency Policy, And Carbon Pricing, Information Paper, IEA, August 2011. Available at https://www.iea.org/publications/freepublications/publication/EE_Carbon_Pricing.pdf (last access on Nov. 21st 2016.)

The role of the industry

The gas compressor based cooling technology industry is a very well established industry and comprises gas refrigerant manufacturers, gas compressor manufacturers and cooling appliances manufacturers. The use of gases poses the biggest environmental challenge to this industry. Until today the gas producers and compressors manufacturers had the key competences to solve the problem of gas replacement possibly developing new kind of compressors or gases that helped the cooling appliance manufacturers to comply with new regulations and market demand. Unfortunately this incremental technology improvement process is not an easy journey and it represents the incentive for developing alternative technologies such as magnetic refrigeration. Indeed, the environmental incentive for developing magnetic refrigeration technology relies on:

- Efficiency of magnetic cooling engine based applications higher than gas compressor based applications mainly thanks to the fact that the magnetic cooling engine can be designed to run between a cold and hot temperature very near to the cold and hot temperature of the final appliance.
- Gas-free operation with no need of any lubricant.
- Low noise.
- Ease of disposal. In particular the absence of gases simplifies the handling of the same at end of use of the appliances.

The above incentives must be delivered at a competitive cost in order to ensure on the long term the mass market success. Recent achievements in magnetic cooling technology at Camfridge ltd., in terms of size and weight have demonstrated the potential cost competiveness and environmental credentials of magnetic cooling technology[9].

Magnetic Cooling Engine Economic Analysis Framework

The magnetocaloric cooling engine is composed conceptually of five main components:

- The permanent magnet, which should produce a magnetic field strength in a given confined volume, and which is sufficient to efficiently activate the magnetocaloric properties of the magnetocaloric materials.
- The regenerator made of magnetocaloric material.
- The electric motor, which moves the magnetocaloric material in and out of the magnetic field.
- The pumps, which pump the fluid around the regenerators and heat exchangers.
- The fluid handling system, which ensures that the fluid moves smoothly around the system.

The formula to compare different system using the same refrigerant could look like as follows:

$$\text{frequency} \times (\text{high field} - \text{low field}) \times \text{volume},$$

where, the frequency can be 0.5Hz for linear systems and some higher value (2Hz-4Hz) for rotary systems. The volume variable takes into account the design/geometry/ precise

[9] R. Luglietti, P. Rosa, A. Pastore, S. Terzi, M. Taisch, “Life Cycle Assessment Tool Implemented in Household Refrigeration Industry: A Magnetic Cooling Prototype Development”, 14th Global Conference on Sustainable Manufacturing, GCSM 3-5 October 2016, Stellenbosch, South Africa.

position in the system of the regenerator which is linked to the peak force experienced by the motor and the geometry of the permanent magnet. In particular, the ratio of "high field volume" to "open surface area" changes as the relative scale of magnet is altered. In general, the bigger the magnet, the better the ratio usually is, although there are also absolute limits to consider.
The first set of qualitative metrics in order to compare different magnetic cooling engines should include:

1. The size of the magnetic cooling engine compared to the gas compressor that are meant to be replaced.
2. The assembly cost of the magnet.

The magnetic cooling engine to be inserted in the final application must, also, comply with target specifications regarding temperature span and efficiency of the final application using it. It is important to notice that the reference specs of the magnetic cooling engine must be referred to the final application specs and not to the gas compressor specs. Indeed, sometimes the so called "compartmentalized technological approach to innovation" induced by very long years of existence of gas compressor technology can confuse the two sets of specifications, thus overlooking the final goal, to produce high efficient, low cost cooling applications and not a product merely replicating the performance of a gas compressor.
The power per cost/size/weight of a gas compressor follows a parabolic-like (sub-linear) curve while the cost/size/weight of publicly known magnetic cooling prototype engine designs follow a linear or quasi-linear function. The comparison of the curves makes possible to identify the power range competitiveness of the magnetic engine based applications with respect to a gas compressor based applications. It is worthy to notice that new regulations based on international agreements such as the 2016 Kigali Agreement, could increase the cost of gas compressor based applications widening the competitive region to high cooling power. Anyway, at the current stage of knowledge about magnetocaloric performances and projected costs, it can be stated that there are no reasons why magnetocaloric cooling engine-based solutions should have a total cost of ownership, i.e. the sum of CAPEX and OPEX, that is more expensive than the current "energy efficiency equivalent" gas compressor based solutions when the cooling power is less than 1 kW.

Is Domestic Refrigeration The Ideal Entry Market Candidate For Magnetic Refrigeration?

The household gas compressors coefficient of performance present declining value as the cooling power decreases. This behaviour can be explained because the absolute value of the friction losses, mainly due to the presence of lubricant in the gas compressor, is small when it is compared to a cooling power higher than few 100Ws but such losses become more relevant at the typical cooling power of domestic fridges, i.e. few 10 Ws[10]. The magnetic cooling engine does not have lubricant. It is, then, reasonable to expect that below 100 W, magnetic refrigeration will be intrinsically superior to the lubricated gas compressor technology.

Moreover, the magnetocaloric engine can be designed to work reliably and in a very robust mode at temperature closer to the final use resulting in a better thermodynamic performance of the appliance. Thanks to this fact, a cabinet connected to a magnetic cooling engine can

[10] D. Beers, M. Benedict, M. Schroeder, O. Abdelaziz, Practical Refrigerated Appliance Design and the problems Posed to Magnetocaloric Machines, Delft Days Magnetocaloric DDMC Science Center, TU Delft, November 2015.

halve the energy consumption. The disposal costs of gas compressor-based appliances are not yet currently fully charged to the end user but they do affect the industry. Before final disposal of the appliance, the presence of the gas compressor imposes strict gas handling procedures. Being gas-free, the magnetic cooling engine fridge will simplify the disposal procedures and, in so doing, reducing the overall costs. Moreover, very recent studies [9,11] also demonstrated that the life time cost of a high efficient domestic fridge using still a prototype magnetic cooling engine and the high efficient fridge using a gas compressor present similar environmental costs, or even lower if the permanent magnet can be recycled at the end of life.

The completion of first pilot tests, for example under the EU FP7 project ELICiT[12], made possible to start the above remembered "path of incremental improvements, refinements and modifications that will ensure the system wide adoption and diffusion".

Acknowledgments

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[11] Bjørk, R., Bahl, C. R. H., Nielsen, K. K., The lifetime cost of a magnetic refrigerator, International Journal of Refrigeration - Revue Internationale du Froid, vol. 63, 48-62 p., March 2016.
[12] See: http://elicit-project.eu/
[13] See: http://www.frisbee-project.eu/
[14] See: http://www.sseec.eu/
[15] See: http://www.drream.eu/