Design and development of magnetic refrigeration prototype for the performance analysis of magnetocaloric materials

T Kanluang\textsuperscript{1,2}, Y Hanlumyuang\textsuperscript{1,2} and R Techapiesancharoenkij\textsuperscript{1,2,*}

\textsuperscript{1} Materials Technology for Energy Conversion and Harvesting Research Cluster, Department of Materials Engineering, Faculty of Engineering, Kasetsart University, 50 Ngamwongwan Road, Chatuchak, Bangkok, 10900 Thailand
\textsuperscript{2} Thailand Center of Excellence in Physics (ThEP), Commission of Higher Education, Bangkok, 10400, Thailand

* Corresponding author’s E-mail Address: fengrct@ku.ac.th

Abstract. Magnetic refrigeration (MR) has been receiving an attention as an alternative system to conventional refrigeration based on vapor compression. Normally, the vapor compression uses hydrofluorocarbons (HFC) and Chlorofluorocarbons (CFC) as refrigerant fluids which damage ozone layers causing global warming. Consequently, the magnetic system has been developed to replace the traditional system to reduce global warming potential (GWP). The alternative cooling technology is based on the magnetocaloric effect (MCE) of magnetocaloric materials (MCM) which are able to change their temperature following magnetic flux density under magnetic field generator. The refrigeration is operated via an active magnetic regeneration (AMR) cycle with rotating magnets. In this work, the magnet assembly has been designed and studied with the aspiration for compact and efficiency. Based on extensive reviews, the magnet assembly model of Okamura et al. provides the conceptual design with optimal compactness and efficiency. Hence, in this study, the magnet assembly design has been developed based on the model by Okamura et al. The magnetic system consists of a soft magnetic composite stator and four neodymium (NdFeB) permanent magnets rotated by motor. The magnetic field performance of the assembly is analyzed using the COMSOL Multiphysics software. The generated magnetic flux density is 0.65 T provided by only 0.9 L of permanent magnets. In addition, the efficiency of the magnet design is represented by a figure of merit parameter, \(\Lambda_{cool}\). Among others, the proposed design exhibit a high \(\Lambda_{cool}\) value of 0.17, which is as high as five times better than the magnet assembly designs by prior work.

1. Introduction

Magnetic refrigeration (MR) is an alternative cooling technology which has been receiving an interest as an environmental friendly comparing to the conventional vapour compression. In contrast to the conventional cooling technology, the process is based on magnetocaloric effect (MCE) of magnetocaloric materials (MCM) which is able to change temperature, under adiabatic conditions, following a modification of magnetic field. The MCM is used as a refrigerant that increases or decreases its temperature under magnetization or demagnetization, respectively. Water is used as a heat-exchange fluid. This principle is known as active magnetic refrigeration (AMR). Among an attempt to develop MR efficiency, three key components are considered including a regenerator, a magnet-generating structure, and a heat-exchange flow system. The magnet-generating system is an important part to generate the magnetic field for magnetizing and demagnetizing MCM. The magnet assembly is one of
the most important and expensive components for the magnetic cooling system. Therefore, the magnet design for a high-performance magnet assembly is important for optimizing the cost and size efficiency of the magnetic cooling system. The magnet design is analysed based on the generating magnetic field, the volume of the magnetization region, and the amount of used magnet material. Magnet design of MR devices have been developed via using three kinds of magnet. The first developed magnetic-field generator was a superconducting electromagnet [1]. Then, a non-superconducting electromagnet was employed [2]. The third design used permanent magnets in magnetic system to generate the field [3].

The employment of permanent magnets in magnet design has been employed by almost all of the recent magnetic cooling prototypes, since they are not required the high electrical power for high-field generation and large electromagnet coils. The permanent magnet designs have been widely studied. The different magnet designs have been reported such as simple magnet circuits [4-5], Halbach magnet structures [6-7], and complex magnet assemblies [8]. In comparison, the efficiency of permanent magnet designs are characterized via a figure of merit parameter, \( A_{cool} \), proposed by Björk et al. [9].

Here, the magnet design will be studied with the aspiration for compactness and efficiency. The computed design of the permanent magnet assemblies will be considered. In comparison to the prior work, the magnet designs will be further analysed and characterized.

2. Magnet designs

The magnet assemblies were successfully designed using the COMSOL. To obtain a compact magnetic generator with relative high field strength, the complex magnet assembly design was developed with compact shape and simple rectangular permanent magnet shapes, with the principle design inspired from the prior work by Okamura et al. [10], Lozano et al. [11] and Monfared [12]. Soft iron magnets were placed between the permanent magnets to reduce the permanent magnet density, control the magnetic flux line and generate concentrated flux density at high field regions in the magnetic gap. The complex magnet assembly was improved to get the higher efficient magnet design with more compact and cheaper. The proposed structures, both simple magnet and complex magnet assemblies, were reported.

2.1. Simple magnet assembly

The standard NdFeB remanence and relative permeability of 1.24 T and 1.05 H/m, respectively, and the relative permeability of soft iron magnet of 5000 H/m were employed in this work. The simple rectangular magnet structure shown in figure 1 was a rotating magnet system consisted of an inner rotating NdFeB permanent magnet centered inside the outer stationary iron yoke. The rectangular NdFeB had a total volume of 1.52 L with a length of 100 mm. The iron yoke had an outer and inner diameter of 135 and 120 mm, respectively. The average magnetic flux density of 0.50 T was created in the gap between the permanent magnet and the outer yoke. The flux line was pushed from the inner magnet to the outer yoke. The magnet design showed the magnetization or high flux density region of 0.64 L, in which a stationary bed of MCM will be placed for magnetizing and demagnetizing cycles for a magnetic cooling system.

![Figure 1](image.png)

**Figure 1.** (a) A sketch of the simple rectangular magnet assembly. The dark gray area indicates NdFeB permanent magnets. (b) The determined structure with magnetic flux density (T). The black arrows show the direction of the magnetization.
2.2. Complex magnet assembly

The complex magnet structure consisted of an inner rotating magnet of four rectangular NdFeB permanent magnets connected with soft iron magnet and an outer yoke of a soft iron magnet as shown in figure 2(a). The assembly was designed to reduce the density of permanent magnet used in the system and increase the average flux density. The flux lines were pushed from the permanent magnets to the connected iron magnet and pushed to the outer yoke as shown in figure 2(b). The magnet design contained a total volume of NdFeB of 0.9 L with a length of 100 mm creating the high flux density region of 0.23 L. The iron yoke had an outer and inner diameter of 135 and 120 mm, respectively. The average magnetic flux density was increased from 0.55 to 0.65 T.

Figure 2. (a) A sketch of complex inner rotating magnet assembly. The dark gray area indicates NdFeB permanent magnets. (b) The determined structure with magnetic flux density (T). The black arrows show the direction of the magnetization.

3. Magnet design characterization

In comparison to other magnet designs, the designed magnet systems were characterized via using a figure of merit, $M^*$, which was firstly proposed by Jensen and Abele [13] as

$$M^* = \int_{\text{field}} B^2 dV \left( \int_{\text{mag}} B_{\text{rem}}^2 dV \right)^{-1}$$

where $V_{\text{field}}$ is the volume of magnetization region or the volume of the region that the high flux density ($B$) is placed. $V_{\text{mag}}$ is the volume of the permanent magnet used with the remanence ($B_{\text{rem}}$). This proposed parameter provides the maximum $M^*$ value of 2.05. It is notable that the magnetic flux density is generated in the gap between the magnets. Consequently, the magnetic flux density is directly proportional to the magnetic field. The relation between the magnetic flux density ($B$) and the magnetic field ($H$) is defined as

$$B = \mu_0 H$$

where $\mu_0$ is the permeability of the free space. The latest figure of merit, $A_{\text{cool}}$, was proposed by Björk et al. [9] defined as

$$A_{\text{cool}} = \left( B_{\text{field}}^{2/3} - B_{\text{out}}^{2/3} \right) \left( V_{\text{field}} V_{\text{mag}}^{-1} \right) P_{\text{field}}$$

where $P_{\text{field}}$ is the fraction of an AMR cycle that magnetocaloric materials are placed in magnetization region. $A_{\text{cool}}$ is proportional to the flux density to the power of 2/3 referred to the adiabatic change of the Curie temperature of magnetocaloric materials by mean field theory scaled the magnetic field to power of 2/3. Here, we used $A_{\text{cool}}$ to characterize the proposed magnet designs comparing to prior works.

4. Discussion

The $A_{\text{cool}}$ of different magnet designs were summarized in table 1. To maximize $A_{\text{cool}}$, the maximum flux density with the minimum amount of used permanent magnet is preferred. The $P_{\text{field}}$ parameter can be measured by the cycle time and the rotating time of rotating magnets. Thus, the efficient motor can provide the $P_{\text{field}}$ as high as 0.90. Nonetheless, the remanence of NdFeB is 1.24–1.44 T depending on the
manufacturing process. If the remanence is increased, the average flux density is increased. So, this is a main problem to compare the different designs.

Table 1. The summarize of different magnet designs

| Magnet designs                      | B (T) | \(V_{\text{field}}\) (L) | \(V_{\text{mag}}\) (L) | \(P_{\text{field}}\) | \(A_{\text{cool}}\) | Ref. |
|-------------------------------------|-------|--------------------------|--------------------------|----------------------|---------------------|------|
| Y shaped magnet structure           | 1.50  | 0.15                     | 4.70                     | 0.90                 | 0.03                | [8]  |
| Single magnet circuit               | 0.93  | 0.09                     | 0.50                     | 0.90                 | 0.15                | [4]  |
| Halbach cylinder                    | 1.03  | 0.07                     | 0.50                     | 0.50                 | 0.07                | [6]  |
| Rotating Halbach-like array         | 1.13  | 0.07                     | 1.50                     | 0.90                 | 0.05                | [14] |
| Inner rotating magnet               | 1.00  | 0.80                     | 0.90                     | 0.21                 | 0.21                | [10] |
| Simple magnet assembly              | 0.50  | 0.64                     | 1.52                     | 0.50                 | 0.13                | This work |
| Complex magnet assembly             | 0.65  | 0.23                     | 0.91                     | 0.90                 | 0.17                | This work |

5. Conclusion

The simple and complex magnet assemblies has been successfully designed with the aspiration for compact and efficiency based on the model of Okamura et al. [10]. The analyses applied the model of AC/DC with magnetic field (no current) of the COMSOL Multiphysics. The complex inner rotating magnet assembly showed the average flux density of 0.65 T by using 0.9 L of permanent magnets. In comparison the efficiency of the magnet design to other works, the designs were characterized by a figure of merit parameter, \(A_{\text{cool}}\). Among others, the proposed design exhibit a high \(A_{\text{cool}}\) of 0.17, which is five times better than the magnet assembly designs by prior work. Finally, the designs were a guideline of the magnet system designs used in the further practical devices.

Acknowledgment

This work is financially supported by Thailand Center of Excellence in Physics (ThEP) Grant# ThEP-60-PIP-MU1. The authors thank Assoc. Prof. Kittiwit Matan for project coordination and guidance.

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