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A review on design and performance of thermomagnetic devices

Ravi Anant Kishore*, Shashank Priya

Center for Energy Harvesting Materials and Systems (CEHMS), Virginia Tech, Blacksburg, VA 24061, USA

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ABSTRACT

Thermomagnetic energy harvesting technology has not received significant attention despite great potential for generating electricity from low thermal gradient near room temperature. This review summarizes the findings reported in literature covering the broad topical areas within thermomagnetic energy harvesting and provides perspective on the potential applications of this technology. The information has been organized chronologically in order to provide systematic understanding of the concepts and evolution of the device designs. Both, active and passive types of thermomagnetic energy harvesters have been included in the paper. The selection of suitable thermomagnetic material is key towards achieving an efficient energy generation device. Therefore, various material compositions have been discussed and their thermomagnetic behavior has been elucidated to provide guidance for their implementation in future devices.

1. Introduction

All forms of energy, such as mechanical, electrical, magnetic, or metabolic, ultimately degrade to thermal energy. Therefore, thermal energy is considered as one of the most ubiquitous forms of available energy. Unfortunately, in most cases, a significant fraction of available thermal energy is discarded as waste heat. Vehicles, manufacturing and power plants, electrical and electronic devices, or the human body emit thousands of joules of heat that is discarded in the environment. According to an estimate by the US Department of Energy (DOE), almost 50% of thermal energy generated from all fuels burned remains unused and is released into the atmosphere. Wasted thermal energy from US industries could generate up to 20% of the domestic electrical supply [1].

Utilizing the wasted thermal energy and converting it into more usable form, such as mechanical or electric energy, has been an interesting area of research for last few decades. Currently, the popular low-temperature thermal energy conversion mechanism is based upon thermoelectric (TE) effect. TE converters utilize Seebeck effect, where a voltage is induced when the hot ends of two dissimilar conductors are connected at a junction [2]. TE converters have relatively low energy-conversion efficiency, ~5% when hot-side temperature is below 200 °C, which limits their application especially where reliability is a major consideration [2,3]. The most common TE converters consist of bismuth telluride (Bi_2Te_3) that exhibits figure of merit (ZT) close to unity [4]. It has been proposed [5] that TE converters should have at least 3 times higher efficiency than the current state-of-the-art to become cost-effective.

A fundamentally different approach for converting thermal energy into other usable form of energy is thermomagnetic energy generation (TMEG). TMEG is based on the effect of heat on magnetic properties of ferromagnetic materials which undergo sharp phase change near the transition temperature. The transition temperature, also termed as Curie temperature or Curie point, of ferromagnetic materials refers to the condition where magnetization disappears and material transforms into paramagnetic state. Rapid change in magnetization around a specific temperature can be used to design a device that converts thermal energy into electrical energy, either directly or indirectly via mechanical energy.

The effect of heat on magnetic properties of ferromagnetic material has been known for a long time. Few Patents issued in late 19th century describe concepts for converting heat into mechanical or electrical energy [6–9]. Unfortunately, the performance of these thermomagnetic devices was low and consequently, they were not used for any domestic or industrial application. In addition, limited studies in 1950s [10–12] demonstrated that the theoretical limit for thermal-to-electrical energy conversion efficiency of thermomagnetic devices was less than 1%. These studies reduced interest in this area for several decades [13]. In past couple of decades, there were some attempts made to revive this technology primarily owing to advances made in design of high performance magnetic materials and understanding of thermal transport interfaces.

With advancements in low-power electronics, the energy requirements for commonly utilized devices have reduced. The wireless sensors, for example, now require less than 1 mW to operate. For

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* Correspondence to: Virginia Tech., 310 Durham Hall, Blacksburg, VA 24061, USA.
E-mail address: ravi86@vt.edu (R.A. Kishore).

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several applications like remote location and hard-to-reach areas, it is quite difficult to power the electronic devices using grid electricity. In such applications, lithium ion batteries are currently used, which limits the durability of electronic devices and presents maintenance challenges. While the need for electrical energy is growing exponentially over time, growth in battery capacity is proceeding along a flattening S-curve [14]. Unarguably, there exists an urgent need for harvesting energy from natural resources. Thermomagnetic devices employing rare-earth magnetic materials can be designed to generate electricity near room temperature under very low thermal gradients. In addition, thermomagnetic devices can also be used as thermal actuators. A recent study by Chun et al. demonstrates that thermomagnetic devices can be used to enhance the cooling rate of solar modules utilized in solar-powered unmanned aerial vehicles (UAVs) [15]. Further, this study showed that thermomagnetic devices can be used to increase the heat dissipation rate of data storage servers [15]. Scaling of thermomagnetic generators to generate higher power can be targeted once the basic understanding of high efficiency design has been established.

The primary aim of this paper is to review the results reported in literature on thermomagnetic energy harvesting and to re-evaluate the potential of this technology. An attempt has been made to organize the information chronologically in order to provide comprehensive summary of fundamental concepts, modeling strategies, and device designs. There are usually two methodologies for converting thermal energy into electrical energy. The first method relies on direct energy conversion by using active thermomagnetic devices. The second method is based upon indirect energy conversion via mechanical energy by using passive thermomagnetic devices. Both these types of devices have been discussed in this paper in two separate sections. The selection of appropriate ferromagnetic material with respect to operating condition is key towards achieving good thermomagnetic energy conversion efficiency. The performance of conventional and non-conventional thermomagnetic materials has been compared and their usability is discussed in the context of current requirements.

2. Early thermomagnetic devices

In 1889, Nikole Tesla patented numerous designs for thermomagnetic motor under US Patent 396121 [6], as shown in Fig. 1(a). He obtained the mechanical energy by a reciprocating or rotary action resulting from combined effects of heat, magnetism, and a spring. Tesla's thermomagnetic motor had an electromagnet or a permanent magnet that generated magnetic field, which interacted with an armature. The armature was attached to an arm, which was free to rotate about a hinge. When armature was heated by a burner and its temperature increased above its Curie temperature, spring pulled the armature away from the permanent/electro-magnet. Eventually, the armature cooled below the Curie temperature and the magnetic force overcame the spring force bringing the armature back to its original position. This process continued as long as heating and cooling cycle continued.

Thomas Edison, in his US Patent 380100 [7], presented the concept as pyromagnetic motor (Fig. 1(b)), where the heat was generated from combustion of coal or wood. He employed thin iron sheet to construct an interstitial armature with interstices or tubes extending longitudinally through it. The armature was mounted vertically using a shaft and was placed between the magnetic poles of permanent or electro-magnets. A furnace was located beneath the armature, which had two outlets that covered the lower ends of some of the armature tubes on the opposite sides. Hot air from the furnace outlets was blown through these two group of tubes and cold air through the remaining group of tubes between the hot tubes. Hot tubes were on the diametrically opposite sides and cold tubes in the middle. The arrangement was such that it did not restrict the rotation of armature. Because of the temperature difference, the magnetization of armature varied among different sections, causing an unbalanced force. This led to continuous rotation of armature as long as armature tubes were periodically heated and cooled.

In 1890, Nikole Tesla introduced a patent for pyromagnetic electric generator [8]. Unlike previous patents, his aim was to produce electric current directly without mechanical motion. As shown in Fig. 1(c), a permanent magnet was bridged by an armature core composed of some iron tubes. Two conductors, in which the electric current would develop, were coiled around the armature core. The central portion of armature core can be heated by a furnace beneath it and cooling can be achieved by the steam coming from a boiler. Alternate cooling and heating of the armature switched on and off the magnetic circuit causing variation in the magnetic field, which ultimately resulted in electrical current in the conductors.

In 1892, Thomas Edison patented another type of pyromagnetic generator [9] that contained bundles of thin iron tubes arranged circumferentially inside two iron rings, as shown in Fig. 1(d). Strong permanent magnet or electromagnets were used to magnetize these iron tube arrangements such that the rings formed the two poles of a long magnet. Each bundle of tubes was surrounded by a winding. A furnace was placed beneath the lower iron ring and a half disk-shaped shield was used to cover lower ends of some of the tubes. The open tubes received the hot air from the furnace and thus heated up. On the other hand, the tubes that were covered by the shield were protected from the heat of the furnace, and therefore they cooled down. The shield was slowly rotated about its axis using a motor so that the tubes were always thermally unstable. Progressive cooling and heating of the iron tubes caused change in their magnetization, which generated current in the windings.

It can be noticed from Fig. 1 that early thermomagnetic devices had very complex designs. In addition, they used iron as the working ferromagnetic material. Iron needs a very high temperature, around 700 °C, for demagnetization. Such high temperature will cause thermal degradation of the permanent magnet. Also, achieving such high temperatures requires combustion of lot of fuel, which questions the economic feasibility of these devices. Last but not least, the thermodynamic efficiency of heat engine is proportional to $\frac{\Delta T}{T}$, where T denotes the working temperature. Ferromagnetic to paramagnetic transition normally occurs in a narrow temperature range, therefore ΔT is small. However, as transition temperature increases the efficiency of thermomagnetic device decreases, which makes iron an unsuitable working material for thermomagnetic devices. Clearly, lack of suitable magnetic materials and complex designs resulted in slow progress of thermomagnetic devices.

3. Active thermomagnetic devices

Historically, the conversion of thermal energy into electrical energy is accomplished in two different ways. The first method is direct energy conversion and these type of systems are called as active thermomagnetic devices. They have been traditionally also called as thermomagnetic generator. The second conversion method is via intermediate mechanical stage and such systems are called as passive thermomagnetic devices. These will be discussed in the next section.

3.1. Working principle

A schematic diagram of thermomagnetic generator is shown in Fig. 2. In its simplest form, a thermomagnetic generator consists of a C-shaped permanent magnet or an electro-magnet, a ferromagnetic material placed as a shunt between the poles of permanent magnet, and a winding around the shunt material. The shunt is alternately heated and cooled through the Curie temperature (T_C) using a heat source and a heat sink. Increase in shunt temperature reduces the magnetization and therefore magnetic flux through the shunt decreases. Decrease in temperature produces the reverse effect. The