Applied Energy 154 (2015) 709–717

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Electrically tunable thermal conductivity in thermoelectric materials: Active and passive control

Albert Massaguer Colomer *

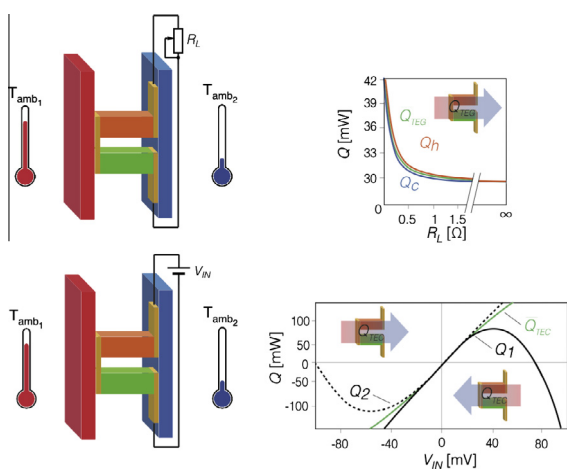
Department of Mechanical Engineering and Industrial Construction, University of Girona, C. de Maria Aurèlia Capmany, 61, 17071 Girona, Spain

HIGHLIGHTS

- TE couples can be used as externally controlled insulators.
- Two control modes can be established: active and passive control.
- Active mode is a good option when a complete insulation is needed.
- Passive mode permits a thermal conductivity increment of $1 + ZT$ times.

GRAPHICAL ABSTRACT

This paper proposes a novel approach to the use of thermoelectric couples, treating them as variable insulators in thermal systems. Thermal conductivity in thermoelectric materials can be externally controlled by electrical parameters such as electrical load or DC voltage in passive and active systems, respectively.



ARTICLE INFO

Article history:
Received 7 April 2015
Received in revised form 12 May 2015
Accepted 20 May 2015

Keywords:
Thermoelectricity
Thermal conductivity
Active control
Passive control
Insulator
Tunable

ABSTRACT

Applications involving the use of thermoelectric materials can be found in many different areas ranging from thermocouple sensors, portable coolers, to solar power generators. Generally, they can be subdivided by the direction of energy conversion. While the Peltier effect is used in solid-state refrigeration, the Seebeck effect is responsible for the conversion of temperature gradients into electrical voltage in energy harvesting systems. However, this paper proposes a novel approach to the use of thermoelectric couples, treating them as variable insulators in thermal systems. Here, we demonstrate that thermal conductivity in thermoelectric materials can be externally controlled by electrical parameters such as electrical load or DC voltage in passive and active systems, respectively. Active mode is a good solution when a complete insulation or a high control of thermal conductivity is needed. Passive mode permits a thermal conductivity increment of $1 + ZT$ times with respect to semiconductor initial thermal conductivity. Results open new doors and new opportunities for thermoelectric materials.

© 2015 Elsevier Ltd. All rights reserved.

* Tel.: +34 972 418 489; fax: +34 972 418 098.
E-mail address: albert.massaguer@udg.edu

http://dx.doi.org/10.1016/j.apenergy.2015.05.067
0306-2619/© 2015 Elsevier Ltd. All rights reserved.

1. Introduction

Thermoelectric (TE) devices are solid-state systems consisting of a number of alternate p- and n- type semiconductor thermoelements, which are connected electrically in series by metal interconnects and sandwiched between two electrically insulating and thermally conducting ceramic substrates. TE systems follow the laws of thermodynamics in the same manner as mechanical heat pumps, vapour compressors associated with conventional refrigerators, or other apparatus used to transfer energy [1]. They can act as coolers, heaters, power generators or thermal energy sensors depending on the direction of current. Due to the lack of moving parts or working fluids, TE technology has been used practically in almost all fields such as aerospace [2,3], instrumentation [4–8], medicine [9,10], industrial [11–15] or vehicles [16–20]. According to the working modes, these applications can be classified into three categories, which are coolers and heaters, power generators or thermal energy sensors.

By applying a voltage DC power source to a TE couple, heat will be moved through the pair from one side to the other. One face, therefore, will be cooled while the opposite face simultaneously is heated. This phenomenon may be reversed whereby a change in the polarity (positive and negative) of the applied DC voltage will cause heat to be moved in the opposite direction. Consequently, TE couples may be used for both heating and cooling thereby making it highly suitable for precise temperature control applications.

Otherwise, when TE couples are subjected to a temperature gradient, flow of majority carriers inside the material occurs from the hot to the cold side resulting in net generation of current. When an electric load is applied across this circuit, useful amounts of power can be generated in response to the temperature gradient applied. It is interesting to note the effect of heat transfer through TE couple with the applied load resistance; when electric load is the lowest the heat transfer is the highest due to the higher contribution of Joule and Peltier effect [21], and vice versa.

Taking into account these behaviours, it cannot be considered just the Fourier heat transport but also the Peltier, Thomson and Joule heat effects. These additional effects can be significantly greater or even opposite to Fourier's law and can be modified by the quantity and direction of current flow. Due to the capability of TE couples to tune the heat transfer flowing through them, another category can be added to the aforementioned applications list; externally controlled insulators.

Exploring the phenomenon at the nanoscale, transport can deviate strongly from the predictions of diffusion theory in macro and microscales [22,23]. With device or structure characteristic length scales becoming comparable to the mean free path and wavelength of heat carriers, classical laws are no longer valid and size effects become important [24–26]. Macroscopic heat conduction assumes that heat propagates at infinite speed, and it does not differentiate between the cause and effect relationship between heat flux and a temperature gradient.

In quantum mechanics, thermal conductivity k depends on the ability of sub-continuum energy carriers, which in solids are electrons and phonons, to travel to exchange this energy. k has contributions from both electrons and hole conductions k_e, and phonons k_p, $k = k_e + k_p$.

The ability to transfer heat by conduction is related to the capability of the electrons and phonons to travel and store/release thermal energy before losing it. When electrons are thermally excited, the mean free path increases, leading to a faster transmission of energy to cooler regions and a greater electronic thermal conductivity k_e. However, in semiconductors, k_e is generally smaller than in metals because there are few electrons available for conduction and they are continually interacting with the ionic lattice [27]. This interaction, due to the temperature gradient, causes energy to flow through the atomic lattice in the form of thermally generated lattice waves or phonons with a net energy flow from the hotter to the colder region. Then, primary heat carriers in semiconductors are phonons, making the lattice thermal conductivity k_p the main contributor to the thermal conductivity.

Heat flow control promises major technological developments in thermal management (e.g. transistors that control charge flow in electronics). Solid-state thermal switches and diodes [28] are particularly desirable for room-temperature cooling systems [29] or efficient building envelopes [30]. While materials with high and low thermal conductivities are available, materials with variable and reversible thermal conductivities are rare. The ability to precisely control the thermal conductivity of a material is fundamental in the development of on-chip heat management or energy conversion applications.

Thereafter, the purpose of this paper is to conduct an exhaustive analysis of thermal conductivity behaviour in thermoelectric materials. We propose two configurations to obtain variable thermal conductivity in thermoelectric materials. Considering that TE couples can work as thermoelectric cooler (TEC) or as thermoelectric generator (TEG), two control modes can be established regarding the external parameter control: active and passive control. Results demonstrate the capability of thermoelectric modules (TEMs) to act as an externally controlled insulator.

As can be seen from Fig. 1a and c, active control occurs when the TE couple works as a thermoelectric heat pump hence heat transfer through it is controlled by input voltage magnitude and polarity [31]. The variation of heat flow is achieved by changing the electric current supplied to the thermoelectric module so an external power source is required [32].

Moreover, as can be shown from Fig. 1b and d, passive control occurs when the TE couple works as a generator hence load resistance controls heat transfer through itself [33]. Electrical power generated due to the Seebeck effect is fed back to the thermoelectric material via an electrical resistor to produce a self-powered Peltier effect so no external energy is required. This will result in an increase of heat flow through the thermoelectric material and consequently a decrease in temperature difference across it. The level of change in heat flow or temperature difference can be controlled by the magnitude of the electrical resistance R_L. Geometrical values related to pellet surface S_{pn} and thickness th_{pn} are 2.3 mm^2 and 2.54 mm, respectively. Additionally, Q_{TEC} and Q_{TEG} represent the mean value of heat transfer across TEM.

2. Methods

To carry out the following study, we have used various theoretical models [21,34–36] that allow us to simulate the electro-thermal behaviour of a real TEM, working as a TEG or TEC. These models are based on the Eq. (1), which can be used with the first law of thermodynamics, and determines the temperature distribution in a thermoelectric material [37].

$$C_p \frac{dT}{dt} = \frac{d}{dx}\left(k\frac{dT}{dx}\right) - \left(T\frac{d\alpha}{dT}\right)J_e\frac{dT}{dx} + \frac{J_e^2}{\sigma} \tag{1}$$

where C_p, T, k, α, J_e and σ are the specific heat per unit volume at constant pressure, absolute temperature, thermal conductivity, Seebeck coefficient, coupled charge current flux and electrical conductivity, respectively.

However, due to the fact that nodal temperatures cannot be determined analytically without knowing the heat flux due to the thermoelectric effects, the models solve these nonlinearities using finite differences and Newton–Raphson methods, which

Download English Version:

https://daneshyari.com/en/article/6686984

Download Persian Version:

https://daneshyari.com/article/6686984

Daneshyari.com