International Journal of Heat and Mass Transfer 93 (2016) 605–611

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

# Solid-state thermal diode with shape memory alloys

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ARTICLE INFO

*Article history:*
Received 13 August 2015
Received in revised form 30 September 2015
Accepted 15 October 2015

*Keywords:*
Experimental analysis
Shape memory alloy
Thermal conductivity
Thermal diode
Thermal rectification

ABSTRACT

Analogous to the electronic diode, a thermal diode transports heat mainly in one preferential direction rather than in the opposite direction. Phase change thermal diodes usually rectify heat transport much more effectively than solid state thermal diodes due to the latent heat phase change effect. However, they are limited by either the gravitational orientation or one dimensional configuration. On the other hand, solid state thermal diodes come in many shapes and sizes, durable, relatively easy to construct, and are simple to operate, but their diodicity (rectification coefficient) is always in the order of $\eta \sim 1$ or lower. Thus, it is difficult to find any potential applications. In order to be practically useful for most engineering systems, a thermal diode should exhibit a diodicity in the order of $\eta \sim 10$ or greater. In this study, a passive solid state thermal diode with shape memory alloy is built and investigated experimentally. The diodicity is recorded at about 90. This promising result could have important applications in the development of future thermal circuits or for thermal management.

## 1. Introduction

Starr, in 1936, was the first researcher to propose the concept of thermal rectification by experimentally investigating a copper oxide rectifier [1]. After his work, several experimental and theoretical studies were performed in order to understand what mechanisms caused thermal rectification [2–12]. With a clearer concept of how thermal rectification is achieved, devices such as thermal transistors, thermal logic circuits and thermal diodes were developed and utilized in different modern fields, for example, cryogenics [13,14], solar energy systems [15,16], micro/nano-electronic cooling [17,18], aerospace industry [19,20] and energy savings for buildings [21,22].

Generally, a thermal diode is the heat transfer analog of the familiar electronic diode, in which is a two terminal device that transmits heat more easily in one direction than in the reverse direction [23]. One simple and familiar example for demonstrating the thermal diode is natural convection between two horizontal parallel plates as shown in Fig. 1. When the lower plate is heated, the heat transfer is driven by buoyancy induced flows. If the upper plate is heated, as there is no fluid motion, the transport is governed by conduction through the gas. It is easy to imagine that the heat transport will be greater when the bottom plate is heated than when the top plate is heated, for the same temperature difference.

The thermosyphon is a common and widely used thermal diode around the world. It can be found in the Trans-Alaskan Pipeline and the Qinghai-Tibet Railway where over 100,000 thermosyphons are utilized in the vertical support columns holding the pipeline or railway above the permafrost [24]. This prevents the pipeline or railway from melting the permafrost, while conversely allowing the permafrost to dump its heat into the ambient through the thermosyphon pillars. Apart from thermosyphon, current techniques for thermal diodes also comprise rectifiers based on adsorption/desorption principles, classical Fourier law, phase change, thermal expansion/contraction (moving contacts), and photon/radiation. Catarino et al. developed a lightweight gas-gap thermal switch using the principle of the adsorption and desorption cycle. Neon is utilized as an exchange gas working in the temperature range of 17–40 K. An active charcoal demountable pump was connected to the switch. An ON/OFF conductance ratio of 220 was recorded at 20 K. However, it should be noted that this kind of thermal switch can only be used or successfully demonstrated in a cryogenic world due to the extremely low thermal conductivity of neon [13]. Strictly, this is a thermal switch rather than a thermal diode (a more detailed discussion about thermal switch is provided in Section 6). By using the classical Fourier law, a certain amount of thermal rectifications can also be achieved between two bulk materials with strongly different temperature-dependent thermal conductivity, and this was first observed in the 1970s [25,26].

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2015.10.045
0017-9310/

## Nomenclature

| | |
|---|---|
| $k$ | thermal conductivity [W/m K] |
| Nu | Nusselt number [–] |
| $Q$ | heat flux [W/m$^2$] |
| $R$ | thermal resistance [K/W] |
| SMA | shape memory allow [–] |
| $T$ | temperature [K] |

*Greek symbol*

| | |
|---|---|
| $\eta$, $\eta^*$ | diodicity (rectification coefficient) [–] |

*Subscripts*

| | |
|---|---|
| *act* | activating |
| *eff* | effective |
| *f* | forward operating mode |
| *H* | high |
| *in* | inlet |
| *L* | low |
| *out* | outlet |
| *r* | reverse operating mode |

Recently, this idea has been re-examined by Dames [6] and Kobayashi [27]. As shown in Fig. 2, the two segments of the junction require two materials. One material (i.e. graphite) shows a strong increase of thermal conductivity with the increase of temperature in segment A, but another material (i.e. quartz) shows a decrease of thermal conductivity with the increase of temperature in segment B. When A is hot and B is cold, both materials are in a regime of high thermal conductivity, and the heat flows more easily from A to B. When the terminals are reversed, both materials are in a regime of lower thermal conductivity, and heat flow is reduced between A and B. As a result, an asymmetric heat flux for the same temperature difference is demonstrated. Kobayashi et al. found that a heat flux ratio of 1.43 between $LaCoO_3$ and $La_{0.7}$-$Sr_{0.3}CoO_3$ in the temperature range from 70 to 100 K was obtained [27]. Boreyko et al. developed a planar jumping-drop phase change thermal diode that retains a large diodicity (rectification coefficient) of phase change diodes with an additional advantage of orientation independence [8]. The jumping-drop phase change thermal diode they developed consists of a planar vapor chamber with opposing superhydrophobic and superhydrophilic plates. The plates are separated by a thermally insulating gasket which also provides a vacuum seal. When the superhydrophilic surface is heated with respect to the superhydrophobic one, the evaporating water carries heat away from the superhydrophilic surface and the vapor condenses on the superhydrophobic surface. Next, a self-propelled jumping motion returns the condensed drops back to the evaporator, which is the superhydrophilic surface, completing the circulation of the working fluid. This process is named as the forward operating mode. Regarding the reverse operating mode, when the superhydrophilic surface is cooler, liquid water is trapped. Thus, no phase change heat transfer takes place in the vapor chamber. In other words, heat mainly escapes through an ineffective conduction across the rubber gasket and vapor space. Their developed planar jumping-drop thermal diode can achieve a diodicity (rectification coefficient) of over 100, together with an orientation independent advantage [8]. In 2013, Ben-Abdallah and Biehs developed a phase-change radiative thermal diode which rectifies heat transport due to the phase transition of the material [10]. Its rectification principle is shown in Fig. 3. As the phase change material $VO_2$ is in metallic phase when the temperature is greater than its transition temperature (~340 K), it creates a heat transfer path which results in a forward mode. Conversely, $VO_2$ is in crystalline phase, like an insulating state, when the temperature is lower than its transition temperature. In its crystalline (monoclinic) phase, $VO_2$ behaves as a uniaxial medium, resulting in a reverse operating mode. With this mechanism, rectification coefficients greater than 70% are found, even at small temperature differences [10]. On the other hand, Chen et al. built up another type of photon (radiative) thermal diode, but they did not utilize any phase change materials (i.e. $VO_2$). Indeed, the photon thermal diode they developed is based on asymmetric scattering of ballistic energy carriers by pyramidal reflectors. Most importantly, they found that this thermal diode not only needs asymmetric scattering, but also nonlinearity. Thermal rectification of 10.9 ± 0.8% was recorded with existing of both pyramids and collimator, while without collimator no rectification is detectable [12]. Recently, another type of thermal diode based on the principle of thermal expansion/contraction as well as thermal contact effect was also studied experimentally [11]. The diodicity (rectification coefficient) of 0.146 ± 0.00334 (or 0.068 ± 0.0025 based on Eq. (3) in this study) was calculated based on measurements of thermal conductivity in both forward and reverse mode. Although the diodicity is not high, the work of Ref. [11] aimed to demonstrate the working principle of using thermal expansion/contraction as well as thermal contact effect for developing the solid state thermal diode.

Since solid state thermal diodes achieve asymmetric heat transfer without the use of liquids or phase change processes, they are relatively easy to construct, durable, and can come in many shapes and sizes. To date, there are five different mechanisms for achieving solid state thermal diodes: (1) using the concept of thermal

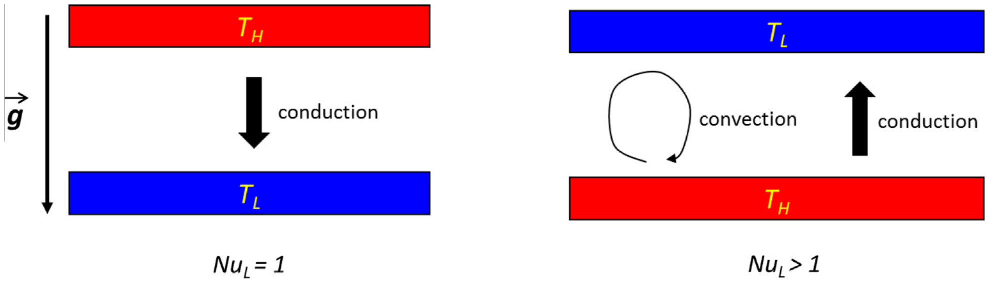

**Fig. 1.** Schematic diagram of rectification in natural convection.