HKIE Transactions

ISSN: 1023-697X (Print) 2326-3733 (Online) Journal homepage: http://www.tandfonline.com/loi/thie20

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HKIE TRANSACTIONS, 2017
VOL. 24, NO. 2, 107–112
https://doi.org/10.1080/1023697X.2017.1312560

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Development of a phase change material (PCM)-based thermal switch

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ABSTRACT
A thermal switch is an ON/OFF heat transfer control device which can be utilised in different modern fields such as cryogenics, solar energy systems, micro/nano-electronic cooling, the aerospace industry and building energy efficiency. In this study, paraffin wax is used to design and build a thermal switch based on phase change material (PCM). When the paraffin wax is heated and melts, one contact plate is pushed to make contact with another plate to turn the switch ON due to the pushing force generated by the volume expansion of the paraffin wax. Conversely, when the paraffin wax does not get enough heat to melt, the condition of the thermal switch is in the OFF state due to an air gap between the two plates. The ON/OFF thermal conductance ratio of the thermal switch is the major figure of merit and is investigated experimentally. The results show that the effective thermal conductivity of the PCM-based thermal switch in the ON state is recorded at 188.7 W/mK, while 6.2 W/mK is obtained in the OFF state. Therefore, the ON/OFF thermal conductance ratio is estimated at about 30.

ARTICLE HISTORY
Received 15 December 2016
Accepted 22 March 2017

KEYWORDS
Paraffin; phase change material (PCM); thermal switch; thermal conductivity; thermal rectification

Nomenclature

k_f	effective forward thermal conductivity (W/mK)
k_r	effective reverse thermal conductivity (W/mK)
k_{eff}	effective thermal conductivity (W/mK)
Q	heat flux (W/m^2)
η	diodicity (-)
dT/dx	temperature gradient (K/m)

1. Introduction

A thermal switch is an ON/OFF heat transfer control device which controls the heat transfer via an "ON/OFF" gate switch [1]. The heat can transfer in either direction in the thermal switch, which makes the heat source and heat sink act as two counterparty terminals: the first terminal and the second terminal. There is a third terminal controlling the gate switch to further control the heat transfer between the first and second terminals. Specifically, the thermal switch decides whether the overall system performs as a conductor or an insulator. When the gate switch is placed in the "ON" mode, the heat is allowed to transfer between the first two terminals and the overall system performs as a conductor; otherwise, the gate switch is placed in the "OFF" mode with no heat transfer, and the overall system performs as an insulator. The effectiveness of a thermal switch is referred to as the ON/OFF thermal conductance ratio, which is the ratio of the effective thermal conductivity in the ON state to the effective thermal conductivity in the OFF state.

In recent years, the use of thermal switches for controlling heat transfer has increasingly drawn attention because of its potential for saving energy. For example, a thermal switch may be integrated into adaptive walls for the thermal management of buildings [2], or combined into solar-thermal collector systems for preventing reverse circulation at night [3]. Thermal switches can also be used for cooling planar electronic components such as microprocessors [4], acting as super heat-spreaders. The aerospace industry [1,5] and cryogenics [6] are two other modern fields where thermal switches can also be applied.

There are four main basic rectification mechanisms: (1) radiation/photons [7,8]; (2) conduction [9,10]; (3) fluid convection [6,11–14]; and (4) physical designs [1,15–17]. Chen and colleagues developed a photon-based thermal diode (i.e. a thermal diode is similar to a thermal switch, but the thermal diode is a two-terminal device, transmitting heat more easily in one direction than in the reverse direction) based on the asymmetric scattering of ballistic energy carriers by pyramidal reflectors; its diodicity (i.e. the effectiveness of the thermal diode, which is defined as $\eta = (k_f - k_r)/k_r$), where k_f and k_r are the effective forward and reverse

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thermal conductivities of the thermal diode, respectively) was recorded at about 10.9 [7]. Ben-Abdallah and Biehs developed a phase-change radiative thermal diode which rectified heat transport by exploiting the phase transitions of vanadium dioxide [8]. The forward mode occurred when the vanadium body was in the metallic phase, while the reverse process took place when the body was in the crystalline phase. With this mechanism, rectification coefficients greater than 0.7 were found, even at small temperature differences.

Theoretically, a certain amount of thermal rectification can be achieved between two bulk materials with very different temperature-dependent thermal conductivities. This was first observed by Jeżowski and Rafalowicz in 1978, who found that the junction's rectification reached 70% for a temperature difference of 40 K [9]. Zhu and colleagues demonstrated temperature-gated thermal rectification using VO_2 beams where the environmental temperature actively modulated asymmetric heat flow, observing up to 28% thermal rectification [10].

For fluid-based thermal switches, gas gap heat switches (GGHSs) using Helium (He), Hydrogen (H_2) and Neon (Ne) have been investigated. In this thermal switch, a copper cylinder was used as the main heat conduction material and placed inside the tube with a tiny space. A hot copper block connected to a heat source was separated from a cold block connected to the heat sink by a supporting shell made from a low heat conductivity material: stainless steel. The ON/OFF thermal conductance ratio of the GGHS was 220, 420 and 3330 for Ne at 20 K, H_2 at 10.7 K and He at 4.2 K, respectively [12,13]. Cho et al. created a mercury micro-droplet chamber thermal switch using air and xenon [14]. However, the fabrication processes are very complicated from the beginning as a result of condensing mercury in the vapour phase, and depositing titanium and platinum nanolayers using magnetron sputtering. Due to safety issues, a fume hood is required during the deposition process. Moreover, several materials (e.g. titanium, platinum and gold) are used in this thermal switch, resulting in a significant increase in cost. With a gas gap of 100 microns, the thermal rectification of the thermal switch filled with air at 760 Torr, air at 0.5 Torr and xenon at 760 Torr are 24, 74 and 129, respectively.

Dos Santos Bernardes developed a physical-based thermal diode/switch based on the principles of thermal expansion/contraction and thermal contact effect, for which a diodicity of 0.146 ± 0.00334 was calculated [15]. Recently, Tso and Chao developed another type of thermal diode/switch using the mechanism of a shape memory alloy, achieving a diodicity of 93.24 ($\pm$ 23.01) [16]. Gaddam et al. demonstrated a liquid-state thermal diode/switch in which the thermal conduction changes due to the displacement of air by the thermal expansion of metallic liquid [17]. The forward mode occurs when the liquid spans the diode to produce a conducting path. The reverse mode occurs when a very thin air gap of 60 microns is created, resulting in high heat flux. Moreover, the metallic liquid (mercury) they utilised is toxic and the thermal conductivity of mercury is very low. A rectification coefficient of only about one was obtained. Ando and colleagues built a thermal switch based on the expansion and contraction of paraffin with an air gap of 0.5 mm which demonstrates an ON/OFF thermal conductance ratio of 100 [1]. Due to being primarily aimed at space applications, the cold plate temperature of this thermal switch was maintained at −20°C. Besides, it should be noted that the obtained ON/OFF thermal conductance ratio was based on an experiment conducted in a vacuum; conductive and convective heat losses were ignored during the determination of the ON/OFF thermal conductance ratio such that a higher ratio can be achieved. Furthermore, their thermal switch is very complicated in fabrication and complex in overall design configuration.

Therefore, in this study, the major objective is to develop another phase change material (PCM)-based thermal switch which is durable (i.e. has thermal and chemical stability), low-cost (i.e. has no unpleasant odour, is non-toxic and can be easily sold at a low price), environmentally friendly, easy to construct, simple in design and competitively efficient. The ON/OFF thermal conductance ratio is examined under room pressure conditions (i.e. more relevant to the conditions in which they will be used).

2. Working principles and description of a PCM-based thermal switch

Copper is known to be a good conductive material for enhancing heat transfer due to its high thermal conductivity of 393 W/mK at room temperature, while air with the thermal conductivity of 0.026 W/mK is a relatively effective thermal insulator [18]. A good heat transfer phenomenon exists when two metal blocks touch each other, while a poor heat transfer occurs with an air gap between the blocks. In this study, a paraffin PCM-based thermal switch using copper powder as the thermal conductive medium in the ON state and the air gap as the thermal resistance in the OFF state are investigated. As shown in Figure 1, the PCM-based thermal switch is basically cylindrical in shape and consists primarily of a top copper plate, a bottom copper plate, a cylindrical PCM actuator, a movable copper contact plate, copper powder, and poly(methyl methacrylate) (PMMA, also known as acrylic) supporting sticks. The diameter of the top and bottom plates is 62 mm, with a thickness of 5 mm. Both plates are separated by four PMMA supporting sticks. The dimension of each rectangular PMMA stick is 22 mm × 58 mm × 2 mm. The PCM actuator filled with the solid form of octadecane paraffin (around 13 g) is located at the centre of the thermal switch, sealed by a rubber membrane to prevent

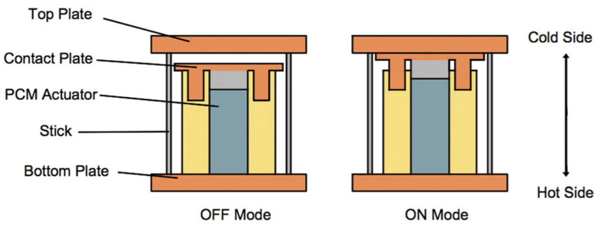

Figure 1. A schematic diagram of the PCM-based thermal switch.

Table 1. The technical specification of the PCM utilised in the PCM-based thermal switch.

Property	n-Docosane
Melting temperature (°C)	42–45
Density (g/ml)	0.778 at 25°C
Thermal conductivity (W/mK)	0.2
Total mass (g)	13

leakage. The n-docosane paraffin ($C_{22}H_{46}$) with a melting temperature ranging from 42°C to 45°C was bought from Sigma-Aldrich. The paraffin has several desirable properties, including a high latent heat of fusion, good thermal and chemical stability, low cost and no toxicity. The technical specification of the paraffin is presented in Table 1. When the PCM is melted, due to the phase change, the paraffin expands its volume and pushes up the contact plate placed above it. In other words, in order to power the PCM-based thermal switch (i.e. activate the ON state), the temperature of the bottom copper plate must be higher than the melting/activating temperature of the paraffin (in this case, the activating temperature of the paraffin is 42°C). When the contact plate contacts the top cold plate due to the expansion of the paraffin, the heat transfer takes place from the hot plate to the cold plate via the copper powder around the actuator. In the OFF state, the paraffin is in the solid phase (i.e. there is no expansion). A small air gap (2.5 mm) between the contact plate and the top plate acts as the insulator. The heat mainly escapes through ineffective conduction across the four PMMA sticks and the air gap.

As shown in Figure 2, on the contact plate there is a small cylindrical PMMA (acrylic) block with a diameter of 13 mm and a thickness of 6 mm that is surrounded by four copper cubes that are 10 mm × 10 mm × 10 mm. When the contact plate is placed on the actuator, the PMMA block is inserted into the PCM actuator connected to the paraffin, while the four copper cubes are plunged into the copper powder. The small PMMA block and the paraffin serve as the moving mechanism, while the copper powder and the four copper cubes serve as the thermal conductive parts of the thermal switch. In order to reduce the thermal contact resistance, thermal grease is applied to the surfaces of the contact and the top plates. A model of the PCM-based thermal switch is shown in Figure 3. The overall height of the PCM-based thermal switch is about 72 mm. An aluminium foil as an insulating

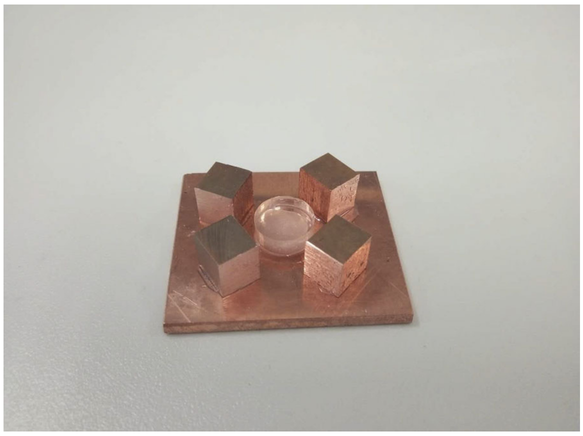

Figure 2. A contact plate.

Figure 3. The prototype of the PCM-based thermal switch.

material is wrapped around the system to prevent undesirable heat loss. Lastly, it should be noted that the average actuation time is about three minutes for the thermal switch to change the state from the OFF mode to the ON mode.

3. Experimental analysis

In order to estimate the effective thermal conductivity of the PCM-based thermal switch, the “cut-bar method” was applied [16]. The effective thermal conductivity through the PCM-based thermal switch is calculated by:

$$Q = k_{eff}\frac{\mathrm{d}T}{\mathrm{d}x}, \tag{1}$$

where Q is the heat flux (W/m^2), k_{eff} is the effective thermal conductivity (W/mK), and $\mathrm{d}T/\mathrm{d}x$ is the temperature gradient (K/m). A schematic diagram of

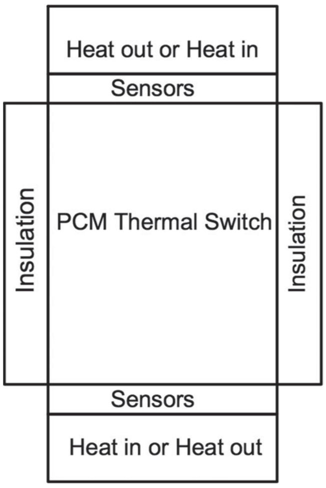

Figure 4. A diagram of the experimental set-up used to measure the effective thermal conductivity of the PCM-based thermal switch.

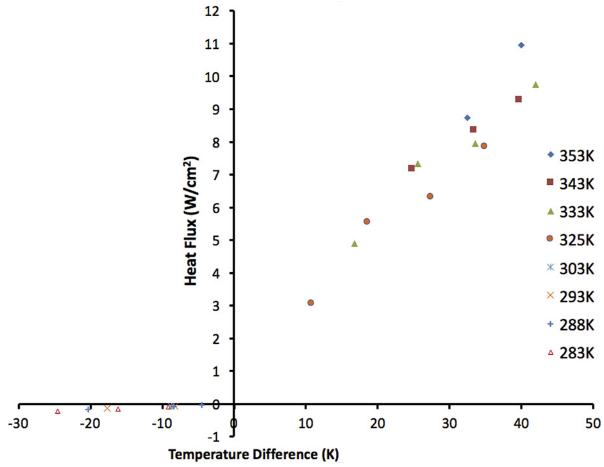

Figure 5. The performance of the PCM-based thermal switch. Note: Temperatures shown in the Legend represent the inlet temperature setting at the bottom copper plate.

the experimental set-up to estimate the ON/OFF thermal conductance ratio (i.e. the effective thermal conductivity) of the PCM-based thermal switch is shown in Figure 4. During the ON-state testing, the bottom circular copper was heated by an isothermal water circulator, while the top plate was cooled by another isothermal water circulator. A heat flux sensor (purchased from greenTEG Ltd.) and a *K*-type thermocouple (purchased from RS Components Ltd.) were inserted in between the bottom copper block and a heat exchanger connected directly to the isothermal water circulator. It was also the same on the opposite side with the top copper block and another heat exchanger. The heat flux was obtained through the sensor by measuring the voltage signals. During the OFF state, the experimental apparatus remained the same, but the bottom copper plate was cooled with cold water while the top plate was heated with hot water. In the experiment, the temperature of the bottom copper plate was tested from 283 K to 353 K at increments of 5 K. The temperature differences between the hot side and the cold side and the heat flux were recorded using data acquisition (DAQ) devices obtained from National Instruments.

The measurement tolerance of the *K*-type thermocouple is ± 1.5°C, while the relative error of the heat flux sensor was about ± 3%. The measuring instruments were calibrated before performing the experiments. Neglecting data acquisition, data reduction (round-off and truncation) and personal operating variations, the uncertainty of the measurement of effective thermal conductivity of the PCM-based thermal switch – which depends mainly on the temperature and heat flux reading– is estimated at about 4%, and this guarantees the credibility of the experimental data.

4. Results and discussion

The major figure of merit of the thermal switch is the ratio of ON mode thermal conductivity over OFF mode thermal conductivity (i.e. the ON/OFF thermal conductance ratio). Figure 5 shows the performance of the PCM-based thermal switch under different testing conditions (i.e. heat flux against the temperature difference between the bottom and top copper plates). It should be noted that the temperature difference is positive when the bottom copper plate temperature is higher than that of the top plate (the ON state) and vice versa (the OFF state). Similarly, the heat flux value is positive when the heat is transferred from the bottom plate to the top plate (the ON state). The results show that a larger temperature difference between two plates leads to a larger heat flux value. The effective thermal conductivity of the switch in the ON state and the OFF state was recorded at 188.7 ± 19.1 W/mK and 6.2 ± 0.5 W/mK, respectively. As a result, the ON/OFF thermal conductance ratio of the PCM-based thermal switch achieved in this study is approximately 30. In addition, it should be noted that the average effective thermal conductivity in the ON state of the switch is much smaller than that of pure copper (386 W/mK at 20°C) due to the major thermal contact resistance between the copper blocks, the thermal conductivity of the copper powder and the minor heat loss to the surroundings.

In this study, the results show that the working temperatures of the heat sink and the heat source (i.e. the top and bottom plates) and the temperature of the paraffin are very important parameters. The effectiveness of the thermal switch is determined by these parameters. In the ON state, the heat flux of the system varies directly with the temperature difference between the heat source and the heat sink, and the temperature of the bottom plate. In the OFF state, the heat flux also varies directly with the temperature difference, but varies inversely with the temperature of the bottom plate. Thus, it can be said that in order to optimise the effectiveness of the system, in the ON state, the temperature of the cold plate should be minimised while the temperature of the bottom plate should be maximised, while in the OFF state, the temperatures of the top and bottom plates should be very close to the melting point temperature of the selected PCM, but the bottom plate temperature should be slightly lower while the top plate temperature should be slightly higher.

In comparison with thermal switches developed by other researchers, the present PCM-based thermal switch shows a comparable performance with simple construction at a lower cost. The thermal switch based on arrays of liquid-metal micro-droplets can achieve a higher ON/OFF ratio of about 129 at 760 Torr (the low-pressure condition). However, the mercury micro-droplets are toxic, so the fabrication processes are very complicated and the cost is high [14]. Compared with the previous paraffin-actuated thermal switch designed for space missions, the PCM-based thermal switch showed an ON/OFF thermal conductance ratio of about 127 when it was tested in a vacuum condition (10^{-3} Pa) [1]. This is because the heat transfer present in the air gap in the OFF state comes mainly from the thermal radiation during the vacuum condition test. Thus, by replacing the atmospheric air gap with a vacuum, the ON/OFF thermal conductance ratio of the current device can be significantly improved due to a decrease in heat transfer in the reverse direction. The thermal conductivity of air decreases linearly with pressure in the range of about 10^{-2}–10^{-6} atm [19], thus it is predicted that the ON/OFF thermal conductance ratio would theoretically increase by a factor of 10^3 in a high vacuum. It should also be noted that the air gaps during the OFF state of the thermal switch in other studies are less than 0.5 mm while the air gap in the current study is 2.5 mm [1,14,17]. In this context, if the present PCM-based thermal switch was tested in a vacuum condition, the effective thermal conductivity in the OFF state can be further reduced, resulting in an enhancement in the ON/OFF thermal conductance ratio. Overall, the present switch performs well in terms of the air gap in the OFF mode and performs comparably in the ON/OFF thermal conductance ratio. Furthermore, it is durable, low-cost, orientation-independent, concise and simple to operate for domestic energy management applications.

5. Conclusion

In this study, a n-docosane paraffin PCM-based thermal switch was designed and built. The ratio of the OFF state thermal resistance over the ON state thermal resistance was estimated by conducting a cut-bar method thermal conductivity experiment under the atmospheric pressure condition. The effective thermal conductivity of the switch in the ON state and the OFF state was recorded as 188.7 W/(mK) and 6.2 W/(mK), respectively, demonstrating an ON/OFF thermal conductance ratio of about 30.

Acknowledgements

The authors would like to gratefully acknowledge Mr Yue Ren, an M.Sc. degree student who graduated from the Department of Mechanical Engineering at The Hong Kong University of Science and Technology (HKUST) in 2016, and Ms Stephanie Rawi, an undergraduate exchange student from the Universitas Indonesia, for their great support and cooperation in developing the PCM-based thermal switch.

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