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Thermal control of electronics for nuclear robots via phase change materials

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Abstract

An effective thermal control is highly desired due to the increased heat generated from tight integration of electrical components. It is more difficult when the electronics are operating in high temperature, narrow space and strong nuclear radiation. In this paper, motor drivers of nuclear robots were taken as a case to study the thermal control methods and their effects on keeping the safe operation of electronics. Phase change materials (PCM) was found could lower the temperature by 20 °C and stabilize below 70 °C for more than 78 min, which was 14 times longer than non-protective mode. Besides, the effect of heat sink on thermal conductivity enhancement was discussed.

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Key words: Thermal control, Phase change materials, Nuclear robot, Motor driver, Electronics

1. Introduction

Robot is the automation equipment integrated with machinery, electronics, control, computer, sensors, artificial intelligence and other advanced technologies. It is especially expected to accomplish tasks, such as underwater welding, nuclear accident rescue in high-temperature, high humidity and strong radiation, which is impossible for human body to access. Since the nuclear disaster happened in 2011 at Fukushima, the development of robots working in nuclear plants has become a cutting-edge project. The more complicated tasks expected on robots, the more complex electronic components and the higher running speed of devices are acquired, which results in much more heat fluxes.

The electronic components highly rely on their recommended operating temperature. The outranging of operating temperature would degrade the system performance and cause logic errors of components. Moreover, it may result in irreversible changes in their operating characteristics. During the rescue

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mission at Fukushima, even though the robot Quince was designed for practical use in dangerous environments, its mission was terminated suddenly due to the thermal accumulation led motor driver overheat [1]. When the temperature increased from 40 ^{o}C to 90 ^{o}C, a 31 times failure rate of electrical resistance were found [2]. Besides, to protect the damage arose from nuclear radiation, a thick and heavy metal shield was usually clad on the electronics. Being limited in such a close and narrow space, the temperature control system requires not only effective heat absorption, but also power-saving, high radiation resistance, light weight, small volume, and free noise.

Since fans and pumps are fragile in nuclear condition, forced air cooling and liquid cooling were beyond of consideration. The phase change materials (PCM) can absorb large amount of heat during the process of phase change without electrical power consuming. PCM also has high latent heat of fusion per unit mass and passive behavior. It has been utilized by NASA to protect the battery from overheating in Mars Rover [3], and a temperature control strategy of mobile phone was proposed by Tan [4]. However, its low thermal conductivity sometimes obstructs its application. Fins, porous matrix and particles with high thermal conductivity were usually used as enhancer to promote PCM's properties [5, 6].

The objective of this paper is to research the feasibility of employing PCM in temperature control of nuclear robot’s motor driver in airtight condition. Experimental setup for compact configuration of drivers was designed considering multiple drivers. Effects of PCM and heat fins in thermal control system were also studied.

2. Results and discussions

2.1. Temperature test of motor driver on a six-legged robot

A typical six-legged robot has 3 motors on each of its leg, and a total of 18 motor drivers equipped in its body. The robot can bear more than 400 kg weight with a maximum speed of 1.5 km/h.[7] An investigation was conducted to monitor the temperature of motor drivers during walking with the loads of 266 kg and 456 kg, separately (Fig. 1a). A flaky Resistance Thermometer Detector (RTD) was attached on the surface of a driver, as shown inside Fig. 1b. The robot was kept walking with the load of 266 kg for the first 95 min, with a 5 min break in the middle. After that, it continued to walk with the load of 456 kg for 20 min. Fig. 1b displayed that the temperature grew fast at the beginning of operation, reached nearly 50 ^{o}C after 48 min, and dropped quickly before the restart of the driver. After then, a large increase of 10 ^{o}C was found within 10 min with increase of the load to 456 kg. The power was then shut off in case of the safety of the driver. This test was conducted in open air at RT, it is predicted that a higher temperature must be achieved in ambient environment.

2.2. Experimental setup

Fig. 2a shows the schematic of experimental setup for testing the temperature control result. To protect electronic devices from outside interference, such as radiation and high outer temperature, a closed system was taken for this test. The airtight box is made of bakelite base, aerogel insulation board, and aluminum tape with an inside dimension of 150×150×100 mm^3.

Fig. 2b shows the overall structure of the scheme. It contains a PCM box with two heaters attached. PCM box was a heat sink filled with PCM. Two heaters were employed to act as two drivers’ hot surface. The support frame was used to provide space for mounting thermal control system. To reduce the contact thermal resistance and air gap, thermal silicone grease was filled between the heat sink and the plate. Fig. 2c and Fig. 2d show the internal structure of the heat sink without and with inside fins.

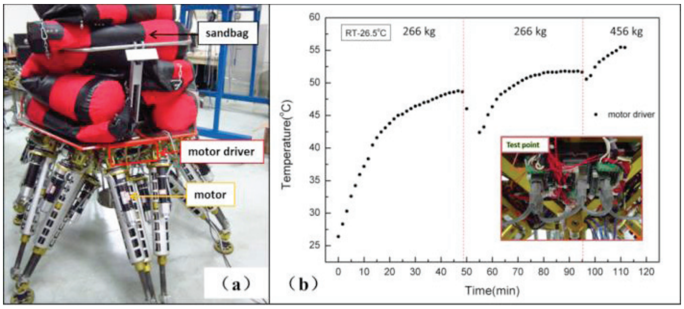

Fig. 1. Temperature test of the six-legged robot (a) experimental six-legged robot; (b) temperature rises with the load and operation time

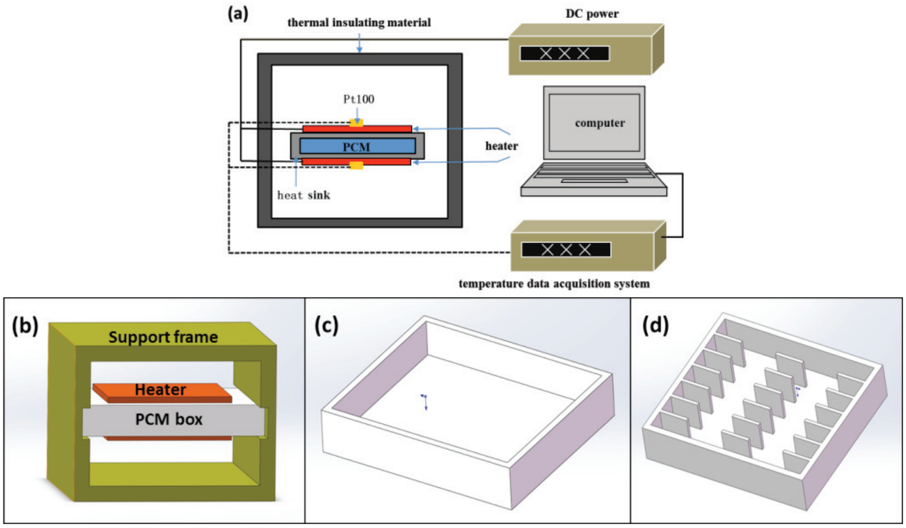

Fig.2. a) Schematic of the experimental setup for multiples drivers; b) temperature control system of multi driver containing a support frame, two heaters and a PCM box; (c) internal structure of heat sink without fin ($60\times50\times10$ mm^3); (d) internal structure of heat sink with 18 fins($60\times50\times10$ mm^3)

DC power was supplied by Agilent 6613C, and RTDs (Pt 100) were used to measure the temperature of motor driver's hot surface. A PC-based temperature data acquisition system (Agilent 34970A Data Acquisition Unit) was used to collect data.

2.3. Radiation resistance of PCM

The PCM used here was a refined paraffin wax (Daqing Kunlun, 58#) with a melting temperature of about 60 ^{o}C and latent heat of 140 J/g. Fig. 3 shows the comparison of DSC curves between irradiated (gamma ray, 4.95×10^{5} rad, 5 h) and original waxes. The phase transition peaks of the two samples are slightly different from each other which are 63.8 °C and 62.8 °C before and after irradiation. The difference of the latent heat of phase change is also small. The latent heat values are 136.2 kJ/kg (before) and 137.6 kJ/kg (after). Therefore the refined paraffin wax can be used for nuclear robot, since the irradiation dose is really a high demand to be considered for the robot working in nuclear environment.

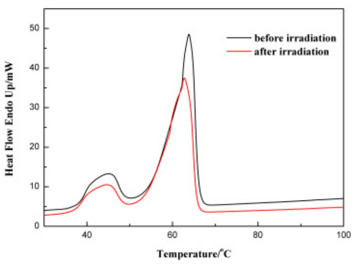

Fig. 3. DSC property of PCM before and after irradiation

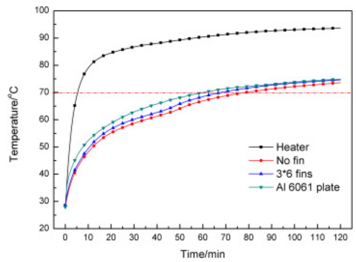

Fig. 4. Temperature-time histories at various cooling structures

2.4. Optimal solution in multiple drivers condition

Here, two drivers were taken for its universality for other more drivers' cases. The temperature-time curves of using different structures of heat sink are given in Fig. 4. No fin represents the heat sink contained PCM (6.5 g) without fins; 3*6 fins means a 18-fins heat sink filled with PCM (6.2 g); Al 6061 plate means a solid plate of Aluminum alloy 6061 which had the same external dimension as others.

Two heaters heated top and bottom surfaces of the heat sink simultaneously. As there was no protective measure, temperature rose up to 85 °C in 20 min, and reached higher than 90 °C at 120 min. Three protective structures showed similar effects on temperature control, with a drop of about 20 °C at 120 min. However, the heat sinks with PCM showed more efficient. Due to the ability of absorbing heat, PCM made more decrease in temperature in the process of heat absorption, comparing with no protective condition. The existence of fins enhanced the overall thermal conductivity of the heat sink, hence heat could transfer faster in PCM, and temperature increased faster in 3*6 fins condition than in No fin condition in the heating process. Considering the comprehensive quality, No fin condition is an optimal way for thermal control.

Table 1. The mass of PCM box and the time consumption of reaching to 70 °C

	Heater	No fin	3*6 fins	Al 6061 plate
m(heat sink)/g	-	47.1	48.1	72.6
Time consumption for reaching 70 °C/min	5.4	78.7	67.8	60.3

As for electronic devices, each additional 2 °C means a 10% drop in its reliability when temperature goes above 70 °C [8], the failure rate of semiconductor device would grow exponentially with increase of temperature. Considering heat resistant ability of electronic components, 70 °C is regarded as a safety point for electronic devices. Table 1 exhibits the mass of PCM box and the time consumption of three kinds of heat sink. It is obvious that heat sink with none-fin got the optimal result in temperature control because it can keep the temperature below 70 ^{o}C for more than 78 min which was 14 times longer than that of non-protective system, and 30% more than Al 6061 condition. Because the robot is very sensitive to the weight regarding the power supply as well as other moving parts, the temperature control system's weight is carefully studied. The heat sink filled with PCM without fins was measured as 47.1 g, which is enough for two drivers' thermal protection. The total weight of 423.9 g is required for 18 motor drivers. This is really a small value compared to the heavy radiation shielding plate and the robot itself, whose weight is ten to hundred kilograms.

3. Conclusion

Based on the measurement of six-legged robot's motor drivers, equilibrium temperature increased with its load and time. On the ambient condition of 26.5 ^{o}C, motor drivers easily reach up to 55 ^{o}C with 456 kg load. Experiments to evaluate the PCM and heat sink for thermal control of electronics in airtight condition were conducted. Paraffin wax was found could be employed to manage nuclear robot electronic components' temperature due to its heat absorptive ability and anti-radiation stability. Heat sink without fin kept the temperature below 70 ^{o}C for more than 78 min with a mass of 47.1 g which was 14 times longer than non-protective mode.

Acknowledgements

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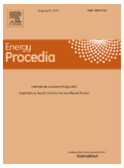

Biography

Weiling Luan received her doctorate in material science and technology in 1998 at Shanghai Institute of Ceramics, CAS. Then she was a postdoctoral researcher at Utsunomiya University in Japan. Now, she is a professor at East China University of Science and Technology. Her research interest includes Micro chemical-mechanical system and the sustainable energy.