Simulation Study on the Heating Characteristics of Ni-Cr Energy Convertor under Capacitive Discharge

Honglan Li[1,*], Yanxiang Chen[1], Xiaoning Bo[1], Guanghui Chang[2]

[1]Taiyuan Institute of Technology, Taiyuan 030008, Shanxi, China

[2]Shanxi Zhongcheng Lianchuang Technology Co., Ltd., Taiyuan 030032, Shanxi, China

*Corresponding Author.

Abstract

Energy convertort is an important ignition component of micro-thrust system, and its heating characteristics under electric excitation are its important technical indicators, which significantly affect the ignition reliability of the energy convertort. To clarify the influence of input electrical energy and structural parameters on the heating characteristics of the energy convertort, the heating characteristics of the Ni-Cr energy convertort under capacitive discharge were studied through simulation methods, and the following conclusions were obtained: the peak temperature of the energy convertort increases exponentially with the capacitance and voltage values. As the length and width of the bridge area increase, the peak temperature decreases exponentially. When there is a V-shaped angle in the bridge area, the peak temperature increases as the V-shaped angle decreases (180 ° -60 °). The substrate thermal conductivity controls the heat transfer of the energy convertort. As the substrate thermal conductivity increases, the peak temperature decreases. It provides important design references for the design of igniters in micro thrust systems .

Keywords: Ni-Cr, energy convertort, temperature, simulation.

1. Introduction

The microstructure energy convertort is an important energy conversion component in the ignition system of micro-thrust systems[1], which converts input electrical energy into thermal energy or plasma energy, excites micro-thrust agents, and achieves control functions such as attitude and orbit adjustment of microsatellites[2]. Compared with traditional energy convertorts, MEMS based energy convertort s have the advantages of small size, high integration, and low excitation energy. Zhang[3] deposited Al/CuO composite thin films on 120 nm thick Pt heating resistors using Pyrex 7740 glass as the substrate and Cr as the adhesive layer to prepare Pt-Al/CuO energy convertort. When the energy convertort explodes, Al/CuO undergoes a violent reaction, with a reaction temperature of up to 2000 K. Shuju Tanaka[4] prepared B/Ti composite thin film energy convertorts using MEMS technology. A constant voltage of 35 V can cause the energy convertorts to explode, and the B/Ti composite film not only undergoes an electric heating effect, but also stimulates the alloying reaction between B/Ti, releasing reaction heat and splashing out reactants, effectively improving the ignition ability. Andréa Nicollet[5] studied the effects of heating area, film layer number, and film thickness on ignition performance based on Ti-Al/CuO energy convertort[6]. By adjusting the heating area of the energy convertort, the ignition time can be increased from 59 μs to 418 ms, and the minimum ignition energy increases with the increase of film thickness. Zheng[7] used finite element method to simulate the temperature distribution characteristics of semiconductor bridge energy convertort under conditions such as electric explosion ignition and electric heating ignition. Under electric ignition conditions, the maximum temperature of the energy convertort does not exceed the melting point of the material. Daeban Seo[8] proposed an energy convertort using glass wafers as the ignition material, with an ignition delay of 17.1 ns at a working voltage of 15V. Wang[9] proposed an energy convertort of Ni-Cr and Al/CuO, which can

generate a flame lasting 416 μs under 60V/47 μF capacitor discharge conditions. Liu[10] also designed an energy convertort composed of Ni-Cr and Al/Cuo, and compared the performance of the new energy convertorts with the traditional Ni-Cr energy convertorts. The research results indicate that Al/CuO nanocomposites can enhance the output capability of Ni-Cr energy convertorts. Among them, Ni-Cr alloy has become the preferred material for microstructure energy convertorts due to its high electrical resistivity, low temperature coefficient of resistance, good mechanical properties, good thermal stability, and easy material availability[11,12]. Song Li[13] used the Neyer D-optimal sensitivity test method to determine that the ignition voltage threshold of Ni-Cr energy convertorts decreases with decreasing size, and the ignition voltage threshold of transducers based on glass substrates will be lower than that of silicon substrates. Wang Kewei[14] conducted a study on the influence of direct current excitation on Ni-Cr energy convertorts. When the current is less than 2.5A, the energy convertorts exhibit thermal conduction, while when the current increases to 3A, the effect shifts to micro convection. Xie Ruizhen[15,16] fabricated Ni-Cr energy convertorts on Prex bulk substrate and conducted research on the influence of structural parameters on firing performance. When the size of the energy convertorts is constant, the firing voltage decreases with increasing thickness, and when the thickness is greater than 0.9 μm, the firing voltage tends to increase. Yan Zhihong[17] designed a Ni-Cr energy convertort with a size of 90 μm × 10 μm × 5 μm and a resistance of 4.3 ± 0.4 Ω. At 10 μ F, the excitation voltage is not greater than 4.8V. Yun Shen[18] studied the electrical explosion performance of different V-shaped Ni-Cr energy convertorts, and found that as the V-shaped angle decreases, the critical explosion time and critical explosion energy both decrease.

The heating characteristics of microstructured energy convertort under electrical excitation are the key factors determining its performance, that is, the temperature peak must be higher than a specific value, and the high temperature duration must be long enough to reliably excite the micro-thrust agents. The heating characteristics of the energy convertorts are not only related to the input electrical energy, but also depend on structural parameters, including length, width, thickness, whether there is a V-shaped angle, and the V-shaped angle. In order to accurately obtain the surface temperature-time variation curve of the energy convertorts, this paper uses finite element simulation method to study the temperature rise characteristics of the Ni-Cr energy convertorts, and obtains the influence of different input energy and structural design parameters on the heating characteristics, providing technical reference for the design of igniters in micro-thrust systems.

2. Simulation Models and Methods

This article takes Ni-Cr energy convertort sputtered on Prex 7740 as the research object, and obtains the heating curve by adjusting the input electrical energy (capacitance value and voltage) and structure size. The influence of different factors on the heating characteristics of Ni-Cr energy convertort is analyzed. The simulation model is shown in Figure 1. The Ni-Cr energy convertort consists of a Ni-Cr metal layer and a Prex 7740 substrate. The Ni-Cr layer is composed of left and right electrodes and a middle bridge region. The electrodes are connected to the external power source, and the bridge region is the main heating area.
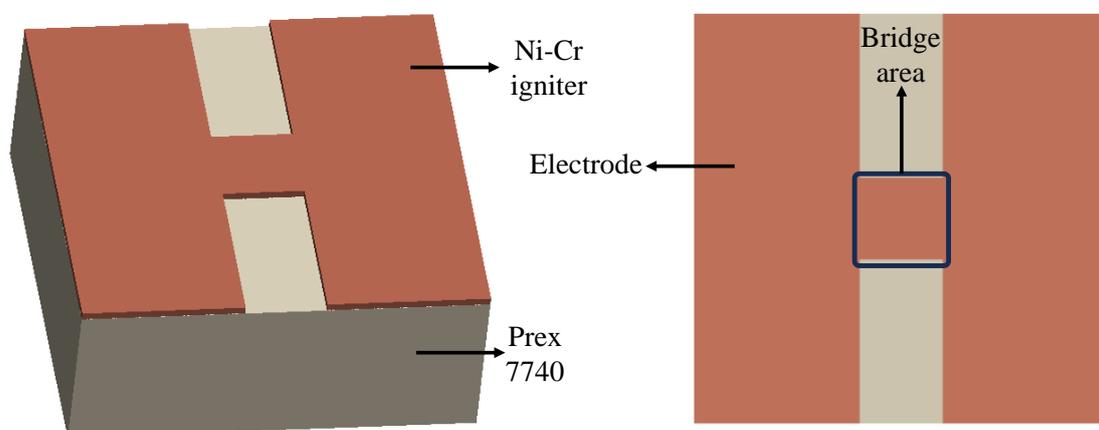

Figure 1 Simulation model

The simulation model parameters are shown in Table 1. The convective heat flux between the energy convertort and air is 5W/(m²·K).

Table 1 Material parameters

Material	Density kg/m³	Conductivity S/m	Heat capacity J/(kg·K)	Thermal conductivity W/(m·K)
Ni-Cr	8820	8.9286×10^5	460	171
Prex 7740	2230	-	182	1.1

3. Results and Discussion

3.1 Research on the Influence Law of Input Energy on the Heating Characteristics

Firstly, an electrical excitation with a capacitance of 10 μF and a voltage of 5-15 V is loaded onto a Ni-Cr transducer with dimensions of 100 μm × 100 μm × 0.9 μm to obtain the temperature growth curve and surface temperature distribution of the energy convertort. The peak temperature variation curve of the energy convertort is shown in Figure 2 (a). As time increases, the temperature rises and reaches its peak. Due to the continuous decrease in energy inside the capacitor, the Joule heat generated by the input electrical energy is less than that of the energy convertort, indicating heat dissipation, resulting in a decrease in the temperature of the energy convertort. As the input voltage value increases, the peak temperature that the energy convertort can reach is greater. The relationship between the input voltage and the peak temperature is shown in Figure 2 (b), and the peak temperature is exponentially related to the voltage.

$$T_{max} = -2954.81 + 2492.87e^{0.087*Voltage}$$
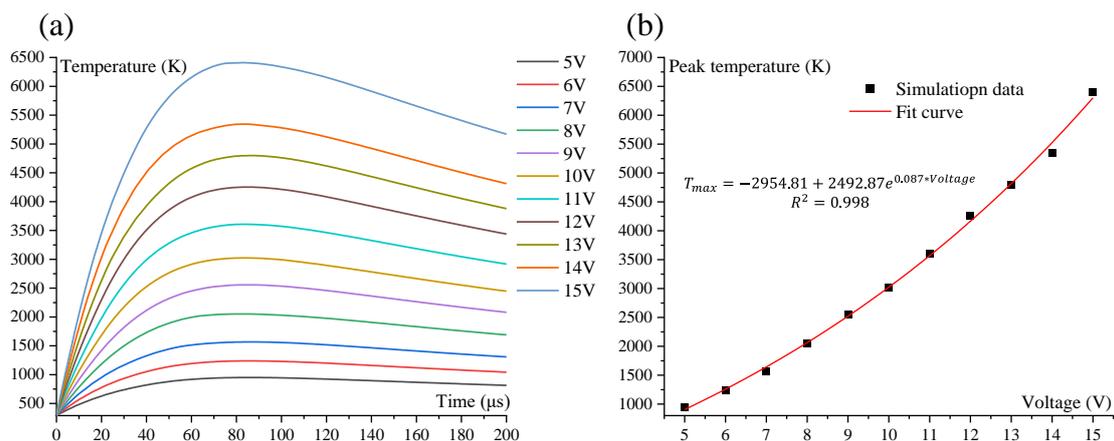$$R^2 = 0.998$$

Figure 2 The effect of input voltage on heating characteristics. (a) Temperature rise curves under different input voltages. (b) The relationship between input voltage and peak temperature.

The heating cloud diagram of the energy convertort is shown in Figure 3. The high temperature area first appears at both ends of the bridge area. As time increases, the high temperature area spreads to the center of the bridge area, and the temperature gradually increases.
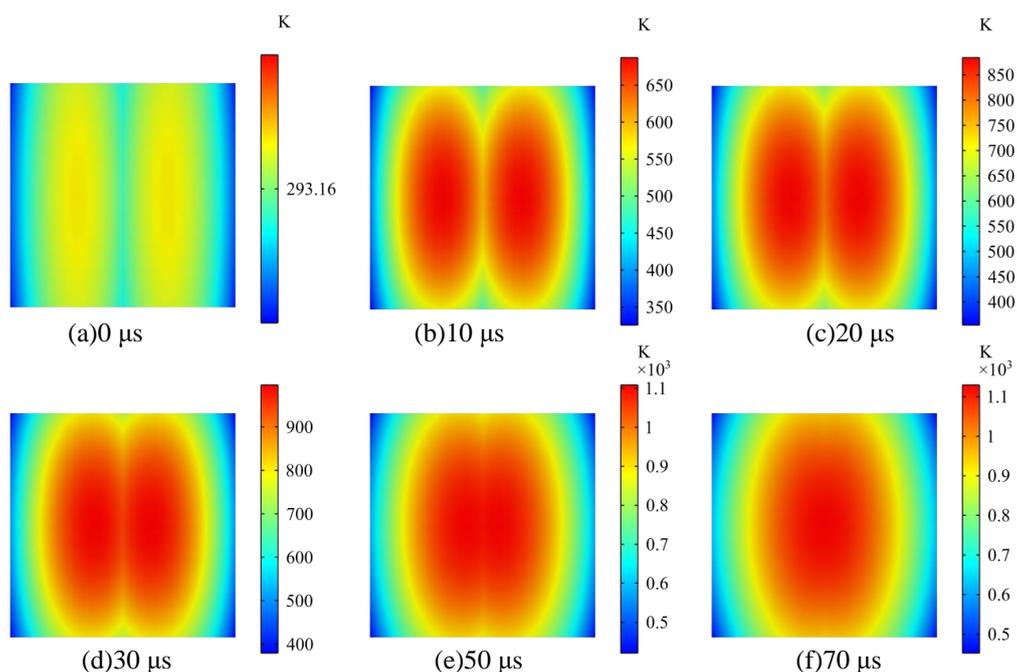
Figure 3 Temperature cloud diagram of the energy convertort

Secondly, the voltage is set to 5 V, and the capacitance values are set to 10μF, 22μF, 33μF, 47μF, 67μF, 100μF to study the influence of capacitance value on the heating characteristics of the energy convertort. The heating curves of the energy convertort under different capacitance values are shown in Figure 4 (a). The energy convertort heats up and reaches its peak under electrical excitation, and then begins to cool down. The relationship between the peak temperature and the capacitance value is shown in Figure 4 (b). As the capacitance value increases, the peak temperature also increases.

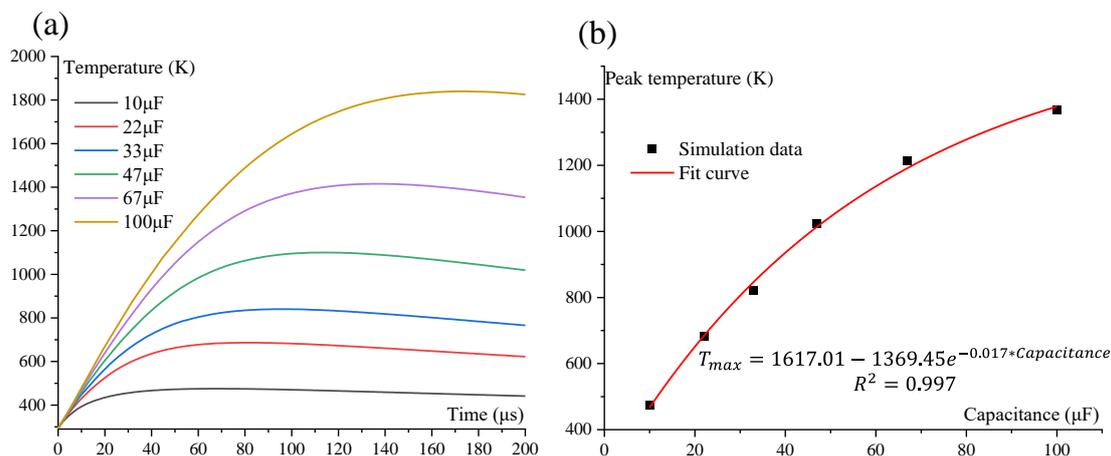$$T_{max} = 1617.01 - 1369.45e^{-0.017*Capacitance}$$
$$R^2 = 0.997$$

Figure 4 The effect of capacitance value on heating characteristics. (a) Heating curves at different capacitance values. (b) The relationship between capacitance value and peak temperature.

3.2 Study on the influence of energy convertort's structure on heating characteristics

In this section, the capacitance value is 33 μF and the voltage is 10 V.

Firstly, investigate the influence of energy convertort's length on its heating characteristics. In the simulation, the width of the energy convertort is 200 μm and the thickness is 0.9 μm. The simulated heating curve is shown in Figure 5 (a). The temperature of the energy convertort increases with time and gradually decreases after reaching its peak. The peak temperature of the energy convertort with different lengths is extracted, and the relationship

between the length and the peak temperature is obtained, as shown in Figure 5 (b). As the length increases, the peak temperature decreases, and the two change exponentially.
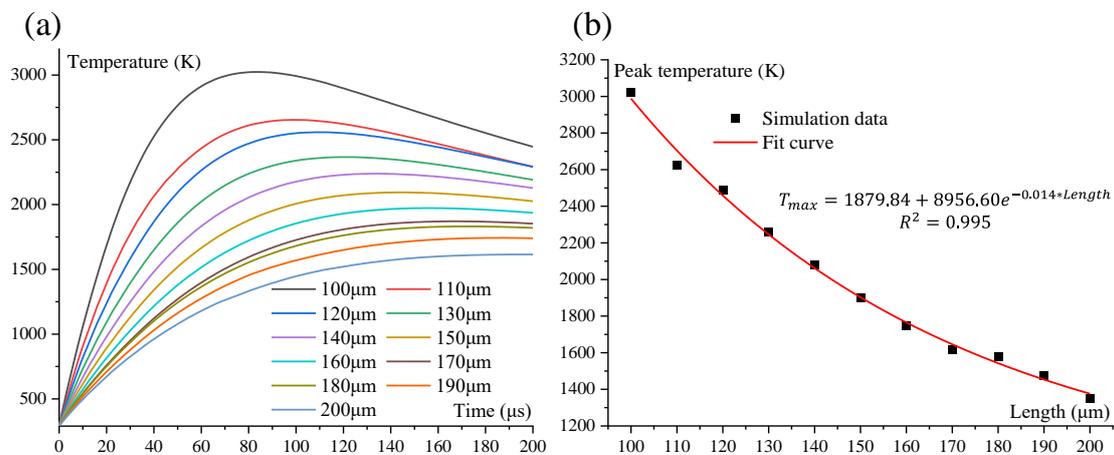

Figure 5 The effect of the energy convertort's length on the heating characteristics. (a) The heating curves at different lengths. (b) Relationship between length and peak temperature.

Secondly, the influence of the energy convertort's width on its heating characteristics is studied. In the simulation, the length is 100 μm and the thickness is 0.9 μm. The heating curve obtained by simulation is shown in Figure 6 (a). The temperature of the energy convertort increases with time and gradually decreases after reaching its peak. The peak temperature of the energy convertort with different widths is extracted, and the relationship between the width and the peak temperature is obtained, as shown in Figure 6 (b). As the widh increases, the peak temperature decreases, and the two change exponentially.
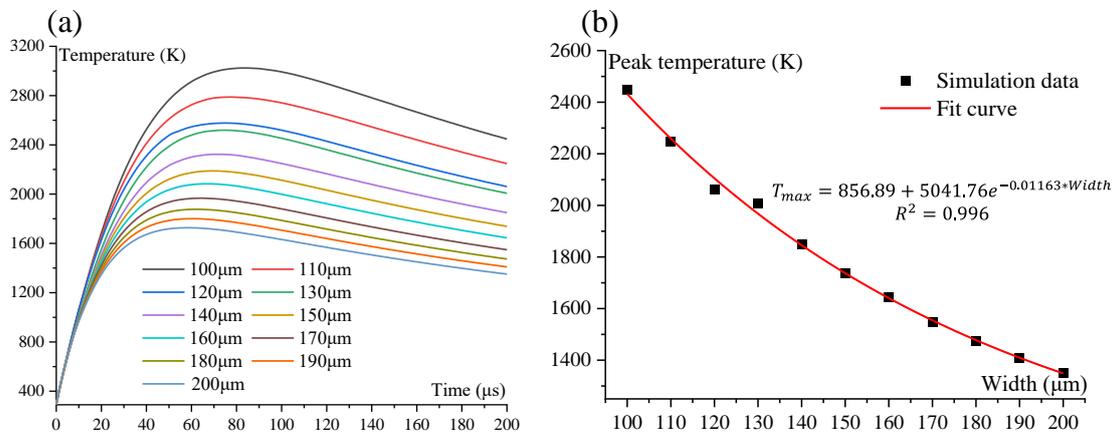

Figure 6 The effect of the energy convertort's width on the heating characteristics. (a) The heating curves at different lengths. (b) Relationship between width and peak temperature.

Finally, a study was conducted on whether there is a V-shaped angle in the bridge area and the influence of the V-shaped angle on the heating characteristics. The simulation model is shown in Figure 7, and energy convertorts with different V-shaped angle were constructed by changing α. In the simulation, the input power is 10V/33 μF, the structure of energy convertort is 100 μm × 200 μm × 0.9 μm, and the angle range is 60 ° -180 ° (with an interval of 30 °), where 180 ° is a rectangular structure.
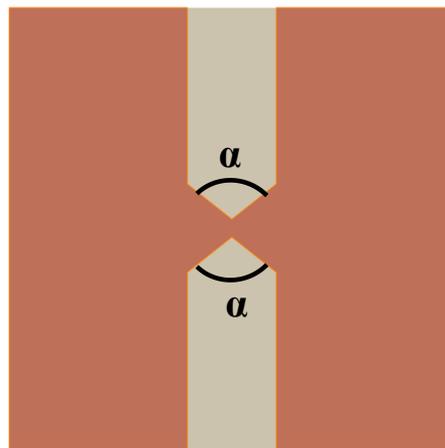
Figure 7 Simulation model of energy convertort with V-shaped angle

The simulated heating curve is shown in Figure 8 (a). The peak temperature is extracted to obtain the relationship between V-shaped angle and peak temperature, as shown in Figure 8 (b). When the input power and the structural parameters of the energy convertort are the same, with the decrease of the V-shaped angle, the area of the energy convertort decreases, and the energy density per unit area increases, resulting in an increase in the peak temperature. The peak temperature changes exponentially with the V-shaped angle.
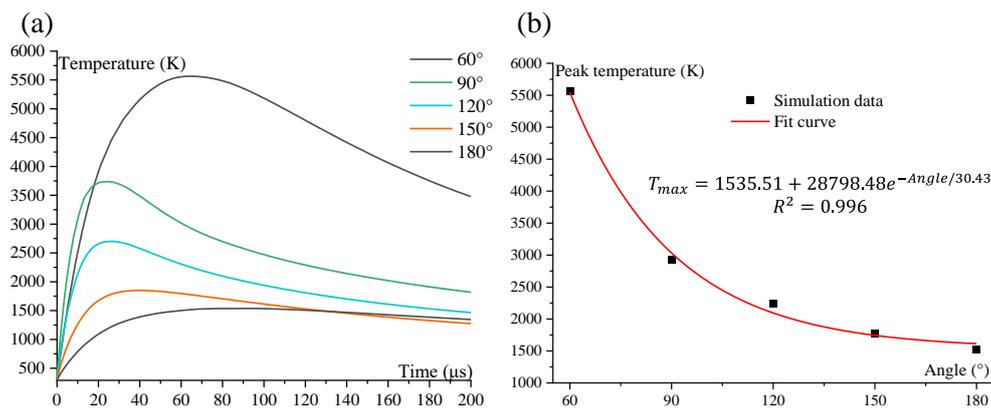

Figure 8 The effect of V-shaped angle on heating characteristics. (a) Heating curves at different V-shaped angles. (b) The relationship between V-shaped angle and peak temperature.

The heating cloud diagram of the energy convertort with a V-shaped angle is shown in Figure 9. Due to the existence of a maximum resistance value in the V-shaped corner, Joule heating first appears at the top of the V-shaped corner. As time increases, the high-temperature region gathers from the V-shaped corner towards the center of the bridge area, ultimately forming a high-temperature region.
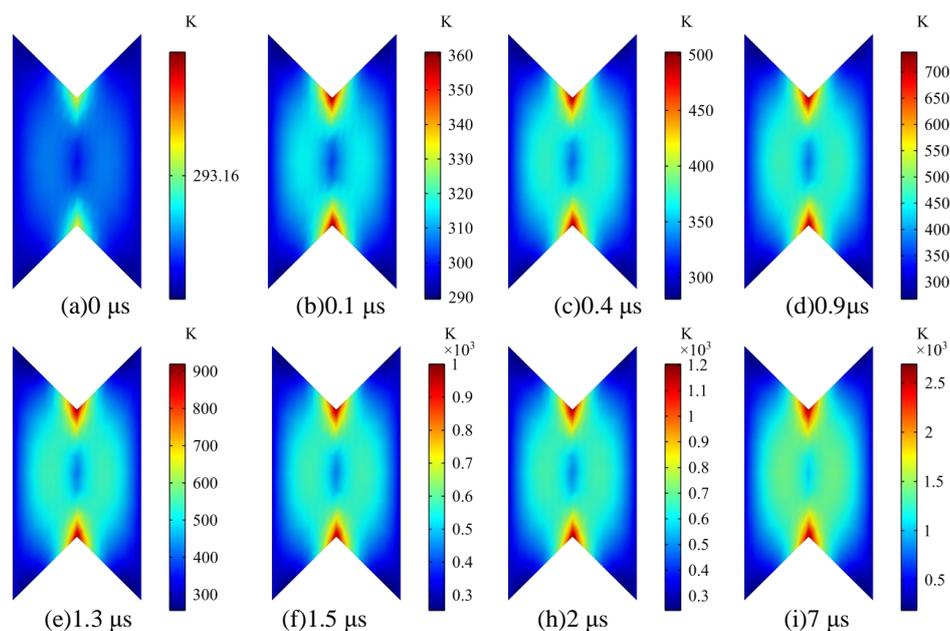
Figure 9 Temperature cloud diagram of the energy convertort with V-shaped angle

3.3 Research on the influence of substrate thermal conductivity on the heating characteristics

The substrate is the structural support carrier of the energy convertort, which has functions such as supporting the structure and controlling heat transfer. The thermal conductivity of the substrate affects the thermal efficiency of the energy convertort. The substrate has high thermal conductivity, which is beneficial for the heat dissipation of the energy convertort and can improve the safe current; The low thermal conductivity of the substrate is conducive to the accumulation of heat in the energy convertort, preventing heat loss and reducing the ignition energy. Therefore, it is necessary to conduct research on the influence of substrate thermal conductivity on the heating characteristics of energy convertorts. In simulation research, the input power is 10V/10 μF, the structure of energy convertort is 100 μm × 100 μm × 0.9 μm, and the substrate thermal conductivity is 1-10 W/(m·K). The simulation results are shown in Figure 10, where the peak temperature decreases exponentially with the increase of substrate thermal conductivity. Suitable substrate materials need to be selected for different working environments to meet the safety and reliability requirements of the energy convertort.

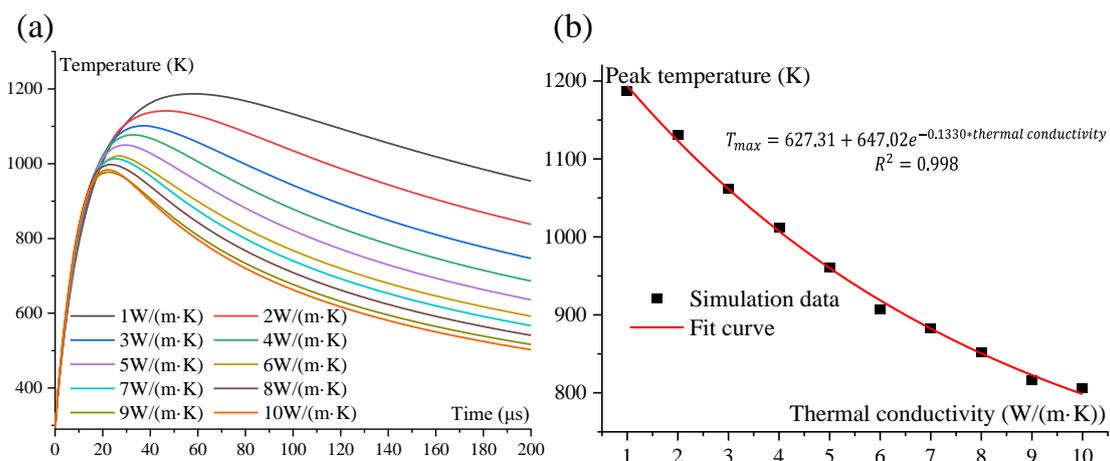$$T_{max} = 627.31 + 647.02e^{-0.1330*thermal\ conductivity}$$
$$R^2 = 0.998$$

Figure 10 The effect of substrate thermal conductivity on heating characteristics. (a) Heating curves under different substrate thermal conductivities. (b) The relationship between substrate thermal conductivity and peak temperature.

4. Conclusion

The microstructure energy convertort, as an important functional component of the igniter in micro-thrust system, has a significant impact on the reliable ignition due to its heating characteristics. To clarify the heating law of the energy convertort under capacitor discharge conditions, this paper obtained the heating curve by changing the input electrical energy and the structural parameters of the energy convertort through simulation methods. By analyzing the simulation results, the following conclusions were drawn:

(1) Under electrical excitation, the energy convertort begins to heat up due to Joule effect, and the high-temperature region gathers from both ends of the bridge area towards the central area, reaching the temperature peak. Subsequently, due to the continuous consumption of energy stored in the capacitor, the Joule heat is less than the structural heat dissipation, and the temperature begins to decrease. As the capacitance and voltage values increase, the maximum temperature of the energy convertort increases exponentially.

(2) As the length and width of the energy convertort increases, the peak temperature decreases exponentially.

(3) When there is a V-shaped angle in the bridge area of the energy convertort, the high-temperature region first appears at the top of the V-shaped angle and spreads towards the center of the bridge area. As the V-shaped angle decreases, the bridge area decreases, the energy density per unit area increases, and the peak temperature of the energy convertort increases.

(4) The peak temperature of the energy convertort decreases exponentially with the increase of substrate thermal conductivity. The substrate thermal conductivity controls the heat accumulation and dissipation of the energy convertort, affecting the reliability and safety of the igniter's function.

References

[1] J. Lee, H. Jo, S. Kim, E. Lee, Y. Son, and A. Lee, "Lab-on-PCB for space propulsion: Integrated membraneless micro-ignitor for MEMS solid propellant thruster," Sens. Actuators, A, vol. 363, p. 114696. 2023.

[2] S. Ahmed khan, "Active attitude control for microspacecraft; A survey and new embedded designs," Advances in Space Research, vol. 69, no. 10, pp. 3741-3769. 2022.

[3] K. Zhang, C. Rossi, M. Petrantoni, and N. Mauran, "A Nano Initiator Realized by Integrating Al/CuO-Based Nanoenergetic Materials With a Au/Pt/Cr Microheater," J. Microelectromech. Syst., vol. 17, no. 4, pp. 832-836. 2008.

[4] S. Tanaka, "Test of B/Ti multilayer reactive igniters for a micro solid rocket array thruster," Sens. Actuators, A, vol. 144, no. 2, pp. 361-366. 2008.

[5] A. Nicollet, "Investigation of Al/CuO multilayered thermite ignition," Journal of Applied Physics, vol. 121, no. 3. 2017.

[6] G. Taton, D. Lagrange, V. Conedera, L. Renaud, and C. Rossi, "Micro-chip initiator realized by integrating Al/CuO multilayer nanothermite on polymeric membrane," J. Micromech. Microeng., vol. 23, no. 10, p. 105009. 2013.

[7] Zheng Zi-long, Xu Jian-yong, Zhang Wen-chao, Ma Ke-feng, Ren Wei, Xian Ming-chun, and Qin Zhi-chun, "An ultrafast temperature response analysis of a MEMS-based igniter using the finite-element method," Energetic Materials Frontiers, vol. 3, no. 1, pp. 18-25. 2022.

[8] D. Seo, J. Jeong, T. Kim, and J. Lee, "A MEMS glass membrane igniter for improved ignition delay and reproducibility," Sens. Actuators, A, vol. 258, pp. 22-31. 2017.

[9] Wang Ke-xin, Hu Teng-jiang, Zhao Yu-long, and Ren Wei, "Research on a MEMS pyrotechnic with a double-layer barrier safety and arming device," Defence Technology, vol. 18, no. 11, pp. 2034-2044. 2022.

[10] Liu Wei, Ren Xiaoming, Xue Yan, Xie Ruizhen, and Liu Lan, "Design, fabrication and performance of enhanced reactive igniter through depositing Al/CuO nanolaminates onto NiCr micro-heater," Modern Physics Letters B, vol. 35, no. 28, p. 2140022. 2021.

[11] Yang Teng-long, Shen Yun, D. A. I. Ji, Zheng Guo-qiang, Wang Cheng-ai, Y. E. Ying-hua, and Shen Rui-qi, "Fabrication and Characterization of a Ni-Cr@Al/CuO Insensitive Energetic Element," Chinese Journal of Energetic Materials, vol. 27, no. 10, pp. 830-836. 2019.

[12] Zhang Bin, Chu Enyi, Rei Wei, " Research Progress in Energy Conversion Components for MEMS Initiating Explosive Device," Chinese Journal of Energetic Materials, vol. 25, no. 5, pp. 428-436. 2017.

[13] Song Li, Zhang Liang, Yuan Changhong, and Xia Wen, "The Ignition Performance of Metal Film Bridge," IOP Conference Series: Earth and Environmental Science, vol. 692, no. 2, p. 022072. 2021.

[14]   Wang Kewei, Duan Buren, Jiang Xiaobin, " Study on the Behavior of Ni-Cr Bridge Film Energy Conversion Element under DC Excitation," Initiators & Pyrotechnics, no. 6, pp. 21-26. 2023.

[15]   Xie Ruizhen, Ren Xiaoming, Liu Lan, Liu Wei, Yu Kexin, and Xue Yan, "Effect of sputtering on bridge region of thin film nichrome heater," J. Phys. Conf. Ser., vol. 2256, no. 1, p. 012012. 2022.

[16]   Yao Xiao-ning, "Effect of Bridge Parameters on the Firing Sensitivity of Ni-Cr Alloy Thin Film Transducer Elements," Initiators & Pyrotechnics, no. 1, pp. 18-20. 2012.

[17]   Yan Zhi-hong, "Preparation and Properties of Ni-Cr Thin Film Bridge with Low Firing Energy," Initiators & Pyrotechnics, no. 5, pp. 29-32. 2011.

[18]   Shen Yun, Xu Jianbing, Wang Chengai, Yang Tenglong, Ye Yinghua, and Shen Ruiqi, "Ignition characteristics of energetic nichrome bridge initiator based on Al/CuO reactive multilayer films under capacitor discharge and constant current conditions," Sens. Actuators, A, vol. 313, p. 112200. 2020.