RESEARCH ON THERMAL DESIGN CONTROL AND OPTIMIZATION OF RELAY PROTECTION AND AUTOMATION EQUIPMENT

by

Na SUO [*] ***and Lina GUO***

Department of Electrical Engineering,
Zhengzhou Railway Vocational and Technical University, Zhengzhou, Henna, China

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Relay protection devices and power automation systems are an important product in the power equipment manufacturing industry. They are customarily divided into secondary equipment for the transmission and distribution industry, and are responsible for protecting and controlling the primary equipment of the power grid and measuring the load of the power grid system. Thermal design is a major research topic for the reliability study of relay protection devices. The paper introduces the thermal design process of the relay protection device processing equipment, from the single-chip, module level, etc. to construct and isolate the airway facilities, and uses the FLOTHERM software to simulate the relay protection device model. Thermal simulation can guide the structural design, optimize the structure, make the single-machine structure more reasonable, and the heat dissipation more effective, improving the reliability of the single machine.

Key words: *single chip microcomputer, relay protection device, thermal design control, automation equipment*

Introduction

The thermal design of relay protection and automation equipment (hereinafter referred to as relay protection equipment) refers to taking active and effective measures to control the temperature rise of components, components and the whole machine so as not to exceed the limits of reliability regulations. Make sure the equipment is operating safely and reliably. In relay protection equipment, power dissipation is usually manifested in the form of thermal energy losses, and any resistive current-carrying element is an internal heat source [1]. Modern relay protection equipment is increasingly becoming a highly integrated system formed by high density assembly and micro-assembly. The heat flow density is increasing. When the equipment is working, if the ambient temperature is not ideal, the improper thermal control will result in the element. Poor heat dissipation of the device, the resistor allows the power dissipation decrease, the thermal noise increases, the capacitance and power factor of the capacitor change, the life is reduced, the parameter drift of the semiconductor device, the performance deteriorates, and even the thermal breakdown. Large levels of temperature gradients can also cause thermal stress distortion in the device and PCB and ultimately lead

[*] Corresponding author, e-mail: suona06@163.com

to fatigue failure. It is generally believed that for every 10 °C increase in the ambient temperature of the device, the failure rate tends to increase by an order of magnitude. This is called the *10 °C rule*. The effect of temperature on the reliability of electronic components is shown in fig. 1.

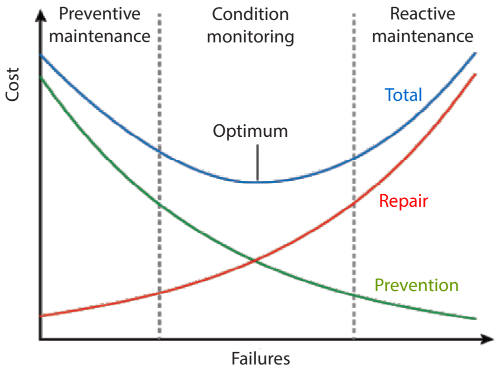

Figure 1. Relationship between component operating temperature and failure probability

Thermal design control of relay protection equipment

The basic way of thermal diffusion

Conduction heat dissipation: Molecular movement by heat transferred from the high temperature part to the low temperature portion. Heat conduction measures are: use a large coefficient of thermal conductivity material part, increase the area of contact with the heating element, and shorten the conduction path.

Convection cooling: Heat flow between the fluid surface, divided into natural-convection and forced convection. Convection cooling measures are: increased temperature difference, increase the contact area of the fluid of the heating element, and increase the flow velocity of the surrounding medium.

Radiation cooling: The heat generated by the object along the line outwardly scattering away. Heat radiation measures are: to increase the temperature difference between the heating element and the surrounding environment, increase the surface area of the heat generating element, and coating surface coating heat the heating element [2].

Design control measures

In the relay protection devices, mainly from the heat resistive current-carrying elements, such as transformers, integrated circuits, power transistors, light emitting devices, chokes and high-power resistor and dissipated into the surrounding medium in the form of conduction, convection and radiation medium. To control or reduce the temperature rise inside the device, it may take the thermal design method for controlling heat treatment, thermal treatment and cooling treatment [3].

Heat source treatment

Component power consumption is one of the sources of heat inside the device. Thermal design methods used are preferably derating components. Derating component is used to make it to work at less than the rated parameters (power, voltage, current) [4]. Further preferably using a high permeability permalloy, amorphous alloy transformer, ultra-low voltage to be working well CPU made small heat of the LED or the like LCD, will directly reduce heat generation.

Laid-type temperature compensation and control components. Firstly, the choice is not temperature sensitive components. Structural materials of different thermal expansion coefficients used such similar components, at high and low alternating tensile and compressive stress is less likely to occur between the interface failure and disintegration. According to this proposed multi-chip resistor use, wound resistance less carbon film resistors; use more monolithic capacitors, tantalum capacitors and less dielectric capacitor sheet; use more MOS, CMOS devices and less germanium tube. Secondly, selection of a temperature coefficient components. The ZDWTA employed in precision and stability as a temperature compensation circuit regulator, the diode having a negative temperature coefficient of the Zener diode in series with a positive temperature coefficient to offset the temperature rise; in most power transistor circuit may be employed having negative temperature coefficient, positive temperature coefficient and the critical temperature coefficient thermistor (*e. g.*, NTC, PTC, CTR) to a variety of temperature compensation. Thirdly, selection of temperature sensitive components. Using a temperature-sensitive component such as the temperature of the thyristor, diode, temperature sensitive for the detection circuit, other circuit embodiments auxiliary temperature control [5].

Rational design of printed circuit boards. Current printed circuit board of the power supply line and a ground line flowing, high calorific value, to ensure the carrying capacity wiring. Considering the heat transfer method, rational and effective components and the guide plate heat out.

Printed circuit board design the following principles: Firstly, the PCB substrate appropriate selection of the thermal properties of copper-clad laminate should have special requirements: to high temperature, thermal conductivity, operating temperature of –23~260 °C. Try to select a relatively good thermal properties of metal core PCB [6], to reduce the temperature rise of the conductor pattern. Secondly, the printed circuit board is disposed the power supply line, ground line, a signal line to be reasonable. Ground may be appropriately widened around the outer frame, in order to facilitate heat dissipation element directly. Thirdly, the use of multilayer, or ground power supply line in the uppermost layer or the lowermost layer of the circuit board, and on the plate to facilitate heat adding means is provided to accelerate heat dissipation. The method of connecting the PCB to the chassis. The PCB ground wire by contact with metal rails, increase heat capacity and thermal conductivity pathways.

Thermal resistance treatment

Resistance heat generating element for explaining the heat transfer capacity to the junction temperature of the external environment, with °C/W is represented. Resistance rating determines the size of the heat sink, effective measures must be taken between the heat generating component and the heat sink lower terminal temperature to form a low thermal resistance path. The relationship between temperature and thermal resistance and power dissipation:

$$R_{ja} = \frac{\Delta T}{P_o} \tag{1}$$

where R_{ja} [°CW^{-1}] for ΔT, when present, the thermal resistance of the heat flow path, ΔT [°C] – the heat flow caused by the temperature difference or drive potential, P_o [W] – the power dissipation components. The total thermal resistance of the device and the heat sink R_{ja}:

$$R_{ja} = R_{jc} + R_{cs} + R_{sa} \tag{2}$$

where R_{jc} is the junction resistance from the device to the mesa shell, R_{cs} – the envelope from the table to the heat sink thermal resistance mesa, and R_{sa} – the mesa to ambient thermal resistance of the heat sink from the surrounding medium [7].

It must be noted previous resistance at the time of the steady-state thermal applicable, non-thermal steady-state thermal resistance when the concept is no longer applicable, must adopt the concept of transient thermal impedance. It is a function of time, when time, transient thermal impedance becomes steady-state thermal resistance.

Reasonable lay-out of components can reduce heat accumulation and improve heat transfer: Firstly, the components are installed in the best natural heat dissipation position. When conditions permit, the internal circuit installation of the chassis should obey the air-flow direction: air inlet→amplifier circuit→logic circuit→sensitive circuit→integrated circuit→small power resistor circuit→heated component circuit→air outlet. Secondly, the high heat elements are placed on a single printed board as much as possible to control the spacing between them, and to seal, isolate, ground, and dissipate heat. Thirdly, the components should be erected on the printed board. Fourth, the component heat dissipation channel should be short, the cross-section should be large, and there should be no insulation or insulation in the channel [8].

The choice of radiator. The main basis for selection is the thermal resistance of the heat sink of the power semiconductor device (the sum of R_{jc} and R_{jc}) and the power consumption of heat, followed by the maximum operating temperature of the junction temperature of the cooling medium of the device. The operation of the main current of the device, according to the highest operating junction temperature, cooling conditions, the thermal resistance, said resistance allows the selection of the radiator. Check radiator standard, choose closer to the heat sink and smaller than this value. Also, considering the environmental requirements, installation location, size, flow resistance, cost and other conditions. In recent years, computer-aided analysis of the choice of the heat radiator technology matured. The most commonly used form of heat sink: plate-shaped, sheet-shaped ribs parallel, interdigitated, or star-shaped. Industrial aluminum and copper materials are two kinds. Copper heat sink surface to be plated, painted or passivated aluminum radiator surface may be painted or anodized. Preferably the self-cooling radiator surface is black, to improve the emissivity, than the black bright radiator heat sink can be reduced by 10-15% of the thermal resistance. Currently ribs parallel and interdigitated plate radiator radiators have been standardized and widely used.

Installation of the radiator. Reasonable install the heat sink, the thermal resistance can be further reduced. Firstly, heat sink in contact with the surface of the component to be flat, smooth, no damage is applied therebetween when installed in a thermally conductive material (grease, aluminum, copper) and pressed into close contact with reasonably effective heat transfer. Secondly, for a self-cooling heat sink fins vertically mounted PCB, facilitate the flow of the hot gas-flow direction, the vertical position than the horizontal position of the thermal resistance can be reduced l5~20%, should be forced air heat sink fins in the cooling air-flow direction. Thirdly, certain elements of the large amount of heat, the heat sealing means may be directly connected to the chassis housing. Fourthly, whether the bolt mounting plate type heat sink or heat sink must maintain the proper pressure on the heat source device. Poor contact force is too small, an excessive contact resistance; both plastically deformed too much force, but the contact surfaces is reduced, or even damage the structure. No specific requirements, the pressure is generally 2~3 KN/cm^2.

Cooling treatment

The method of cooling process is: natural air, forced air, forced liquid cooling, evaporative cooling, heat pipe heat, thermoelectric cooling, cooling vortex, and magnetic refrigeration. According to engineering practice allowable temperature, component assembling method and lay-out of the work environment and other factors and the total calorific apparatus, equipment comprehensive analysis, select the appropriate cooling. Several cooling unit areas of the maximum power consumption in tab. l.

Table 1. Maximum power consumption of several cooling methods

Cooling method	Maximum heat dissipation per unit heat transfer area [wcm^{-2}]
Natural air cooling	0.08
Forced air cooling	0.3
Air cooled plate cooling	1.6
Liquid cooled plate cooling	16
Boiling cooling	5000

Direct cooling. Direct cooling is in direct contact with the refrigerant components, primarily for heat dissipation by conduction and convection methods. Firstly, the natural air cooling. After the heated air around the heat source temperature, the density becomes small heat flow upward buoyancy. Natural cooling without special advantage is that the duct, no noise; disadvantage is the low efficiency of heat dissipation, heat transfer coefficient α is 6~13 kcal/hm^{2}K. It is only suitable for high current devices smaller device or simply the rated current. It is noteworthy that when the gap between the components is less than 3 mm, almost stopped natural-convection, conduction and radiation heat will be the main mode [9]. Secondly, forced air cooling. Forced draft cooling air can be divided into hair and cooled using cooled ventilation equipment heat source evenly distributed when; employ non-uniform distribution of air-blast cooling. Or into lateral longitudinal ventilation and cooling air-flowing through the ventilation cooling in the direction of the heat generating element. Engineering practice based on equipment specifications may decide fan space, heat, air-flow, pressure, noise, air duct trade-offs, to the structure and installation. Direct forced air cooling is a common cooling method, compared to the indirect cooling method, there is a simple structure, less equipment, low cost, used for high heat flux applications, as applied to the rated current value is 50~500 A device. Forced air cooling using fans to force air through the radiator, the flow rate is generally less than 6 m/s, α reach 35-52 kcal/hm^{2}K, is 2-4 times from the cold heat dissipation efficiency. The relationship between wind speed and air resistance curve shown in fig. 2.

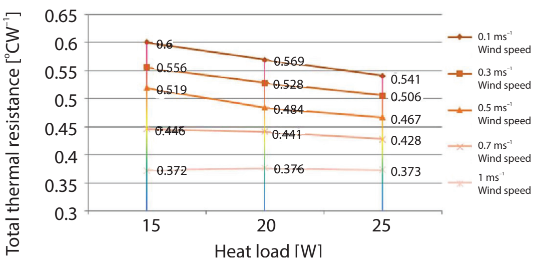

Figure 2. Wind speed and thermal resistance

Indirect cooling. Component indirect cooling is not in direct contact with the refrigerant, the heat transfer method by cold plates, heat exchanger or heat pipe. Firstly, according to the different refrigerant cooled cold plate is divided into: the liquid-cooled and air-cooled. Cold air-cooled refrigerant to the air, generally from the floor structure, ribs, cover and blocked composition. Ribs are main parts of the cold plate, is an integral part of the surface of the base diffusion, fin material is generally copper or aluminum, there are a variety of different structural parameters may be selected according to the shape of the fins of the cooling environment, the ribs spacing, rib height and rib thickness. Air-cooled cold working pressure should be less than 2 MPa. The advantage of simple structure, easy to implement. Disadvantage is the limited cooling capacity, the larger the size of the structure, the heat dissipation efficiency is much lower than the liquid-cooled cold plates, often used in small electronic devices may be used if necessary, as the chassis side plate. Liquid-cooled cold refrigerant liquid (such as water, ethanol and the like), aluminum cold plate material or size often copper, cold plate, the shape of the flow passage, may be determined according to the size of the space, the amount of heat and pressure of the refrigerant. The refrigerant is generally carried out cold working environment selection, focus refrigerant freezing point, boiling point, specific heat, thermal conductivity, heat of vaporization, dynamic viscosity. Liquid-cooled cold plate heat flux density of up to 45×103 W/m^2, commonly used in high power radiating device. Liquid-cooled cold plate cooling efficiency, a large heat flux density, uniform heat load, the temperature gradient is small, compact and light weight. Cold plate design considerations to pump pressure, refrigerant flow rate and the secondary cooling temperature, cooling the surface temperature of the refrigerant and the like.

Secondly, the heater is cooled. Depending on the refrigerant can be divided into: water-cooled, oil cooled, ebullient cooling type. Water-cooled heat exchanger, the flow rate generally take 4~5 Lpm, α reach 200-2000 kcal/hm^{2}K, the advantage of high thermal efficiency, low noise; disadvantage is the need for water cooling and circulation device, and easy to dew condensation, water leakage, electrical corrosion. High heat exchange efficiency of the water-cooled heat exchanger, convective heat transfer coefficient which is about 150 times more than natural air heat transfer coefficient. Generally applicable to the current capacity of the device 500 A in the above. Oil cooling heat exchanger, α reaches 200-800 kcal/hm^{2}K, advantage is not easy freezing, no water treatment equipment, the drawback is a low cooling efficiency, complicated structure and inconvenient maintenance. Oil cooling radiator heat dissipation efficiency between the water cooler and the air-cooled radiator, a cooling medium with multiple transformer oil. Boiling refrigerant is cooled (*e. g.*, freon) is placed in a closed container, performed by a phase change technique cooling medium. It has a high heat capacity, α reach 3000-70000 kcal/hm^{2}K, several times higher than the volume of the cooling efficiency of the oil cooling or water cooling, ten times higher than that of air, so that the ebullient cooling device is smaller than the capacity of the oil cooler with much more, but the system is complex and expensive. Commonly used in harsh environments outdoor cabinet cooling system. At present, foreign more mature type of cooling equipment suppliers APW, RITTAL and so on.

Thirdly, the heat pipe transfers heat. A heat pipe is a hollow pipe structure of a vacuum sealed, filled with a sintered metal, metal felt and a large amount of heat transfer during evaporation of low-boiling liquids (*e. g.*, methanol), and the like when the wick condensed liquid back to the starting point of the inner tube. After evaporating the heated working fluid evaporating part, the slight pressure difference between the steam is condensed to quickly transfer portion, and quickly remove heat, the vapor is cooled in the condensing section and accumulated condensed into liquid, so that under the effect of suction Mao the working fluid back to the evaporator portion, so the cycle than, accomplished automatically heat conduction of the heat pipe. An application example is shown in fig. 3. Heat pipe heat transfer hundreds of times larger, faster thermal response than the same volume of solid metal, long distance transmission, the heated portion and the heat radiating portion can be isolated, simple structure, long life, low failure rate, further comprising a thermal switch and a thermal diode characteristic. In operation, a plurality of heat generating members may be connected to one end and the other end connected to a heat sink, chassis, or other cooling devices. The thermal resistance of up to 0.001 °C/W, heat transfer more than 50 kW. Mainly used in high energy density in electronic device components or the steam bath

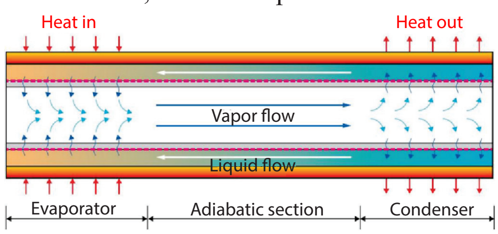

Figure 3. Application examples of heat pipe technology

room temperature state. It is noteworthy that the heat pipe itself does not heat, must also co-operate in condensing heat sink in order to end the final heat to dissipate.

Fourthly, other cooling methods. Also known as thermoelectric cooling thermoelectric cooling. A refrigeration process utilizing a thermoelectric effect, *i. e.*, Peltier effect. Its cooling effect depends on the thermoelectric power of the two materials. Semiconductor material having a high thermoelectric potential, can be successfully used to make a small thermoelectric cooler. Refrigeration thermocouple element substantially consisting of *N*, *P*-type semiconductor shown in fig. 4. Copper and copper conductors with *N*-type semiconductor and the *P*-type semiconductor connected in a loop, copper and copper conductors only act as electrically conductive. In this case, a junction becomes hot and the other cold one contact. If the current direction is reversed, the cold junction points reciprocal action.

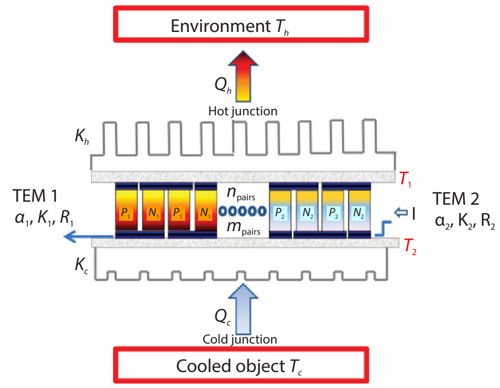

Figure 4. Basic thermocouple

Thermoelectric refrigerator cooling temperature range of –20 °C to room temperature. Due to the small cooling capacity single stage thermoelectric cooler, the temperature difference is 50~60 °C. In order to obtain greater cooling capacity and lower cooling temperature, a temperature difference often multilevel electrical device connected in series, parallel, or series and parallel connection. When using a thermoelectric refrigerator provided cold electronics required to provide a surface higher than the ambient heat and a refrigeration system to pump heat from the cold to the hot face. A small thermoelectric cooler cooling capacity while the high power consumption, cooling should not be so large and massive amounts. However, due to its flexibility and strong, easy to easily switch cold, very suitable for miniature refrigeration.

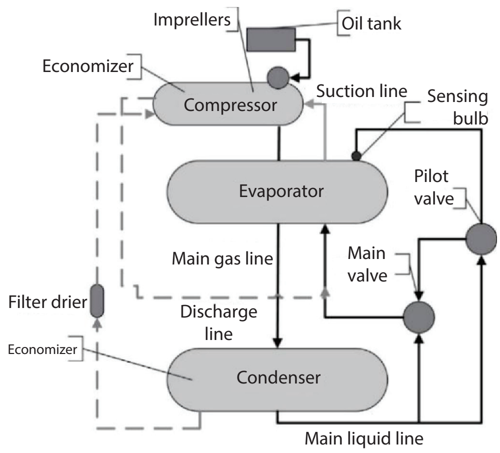

Figure 5. Typical application of a flow chiller

Eddy current refrigeration. Compressed air (usually 0.55~0.69 MPa) by cooler air intake vortex flow is generated incident vortex air-flow at a rotation speed of 106 rpm screwed into the lumen along the wall, to the terminal after a small portion of air through the needle valve to heat air spilled manner, the remaining air continues to turn around in a cyclonic motion as the center of the outer vortex. Meanwhile, the vortex flow inside the exchange to the external energy into swirling flow through cold flow generator and the central cold air outlet bleed. It is reported that when using a pressure of 0.69 MPa, inlet air temperature of 21 °C, single refrigeration vortex tube up to 1512 kcal/h, temperature was lowered bleed 45 °C. Typical applications are shown in fig. 5.

Vortex refrigerator no losses moving parts, using only one vortex tube through the interior of the filter, is converted into conventional compressed cool air evenly distributed in the cabinet. Cold air-flow inside the cabinet is formed a slight positive pressure, dust pollution, especially for harsh environments. Strictly speaking vortex cooling also within the scope of the direct cooling.

Relay protection and automation control equipment thermal design example

Single machine thermal design

The device is a single 3U of standard 19 inch. Apparatus at full load, five internal modules, a power supply module, a CPU module, three user modules. Equipment total power consumption of 140 W. Wherein the CPU module is a chip main heat 5 W, 51 W, chips; three user modules, each heat of 25 W, the chip discretely distributed on the circuit board, the chip is the highest heat consumption 5 W. Total power module power 250 W, efficiency of 78-79%, the heat consumption of about 68 W, the minimum ventilation requirements of the power supply module is fully loaded 20 CFM. The device temperature operating –10~55 °C. CPU module with three user modules required ventilation amount :

$$Q_f = \frac{\Phi}{\rho C_p \Delta t} \tag{3}$$

where ρ [kgm^{-3}] is the density of air, where the election 60 °C, air density of 1.06 kg/m^3, C_p [Jkg^{-1}°C^{-1}] – the specific heat of air C_p = 1005 J/(kg°C), Φ [W]– the total power loss (heat flux) Φ = 85 W, Δt [°C] – the cooling air inlet and outlet temperature Δt = 10 °C initially here. After calculating $Q_f = 7.979 \cdot 10^{-3}$ m^3/s = 16.906 CFM. Considering the need to go through the air-flow inside the module, the system pressure drop along the larger, plus the local resistance of the air duct sharp turning, wind pressure is relatively large, and therefore, the range of allowable size, the choice of a sufficient amount of ventilation and the maximum static pressure fan.

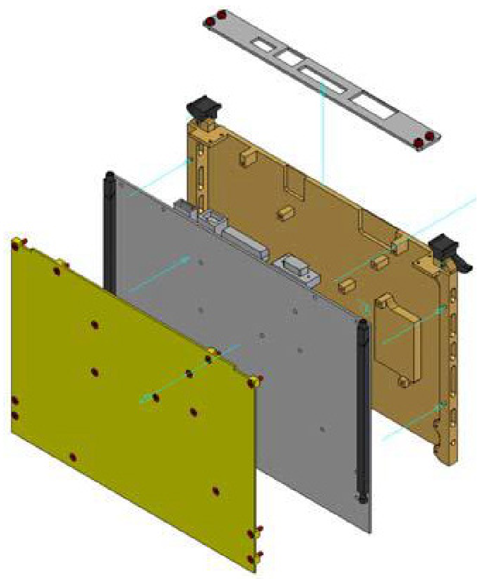

Figure 6. Module exploded view

Module thermal design

In order to balance the vibration resistance of the device module and the electromagnetic compatibility of the two-sided device, the module is in the form of a shield, as shown in fig. 6.

For more efficient cooling module, the heat dissipation module employs a form of air-cooled heat conductivity increase. The heat flux density in the module than 0.4 W/cm^2 components, in the corresponding position on the milled stepped shield, insulating thermal pad affixed to the top surface of the device, the device is part of the heat conducted to the shield case, and then transmitted to the chassis via a guide. The frame emits heat by forcing air cooling and conduction. Module during thermal design, the structure design and circuit design required with reasonably good component dispensing position, the device will send a small amount of heat on the air, a large amount of cloth downwind heat to improve heat exchange efficiency; clear heat high density position of the device, the installation height of the device, the device to reduce the gap and step, controlling the amount of compression of a good insulating thermal pad, thermal conduction is reduced.

Simulation and optimization

By changing the internal frame structure of the equipment, the upper and lower side panels of the frame are extended at the air outlet of the fan, and the air duct baffle is added, so that the closer the air outlet of the air duct and the air outlet of the rear panel is, the better the heat environment inside the device is, and the heat is dissipated. The more significant the effect, as shown in fig. 7.

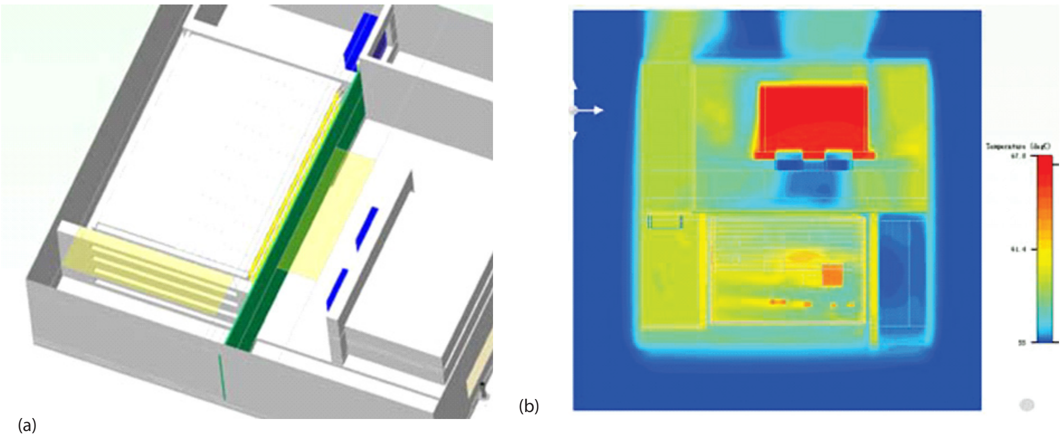

Figure 7. Model and simulation results after duct isolation

Conclusion

Following the thermal protection device design is a very complex work, a lot of problems to be solved, not only to consider the relationship between the thermal diffusion structure with the interior space of the device, but also consider the ventilation openings and electromagnetic compatibility, the contradiction between the level of protection. At the same time due to equipment miniaturization trend, more and ask us early intervention microscale heat transfer from the point of view of how the initiative for effective heat transfer, especially aggressive heat treatment and thermal treatment, thereby improving the thermal diffusion inside the device conditions, supplemented by appropriate refrigeration technology rational use predetermined low temperature obtained over the soaking effect.

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