Structure Optimization Design for Evaporation Substrate in Natural Cooling System Based on the Application of Power Electronics Equipment

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Abstract. Based on simulation, the structure optimization of a Cu evaporation substrate in natural cooling system is conducted, which can be used in power electronics equipment. The relationship between the welding area ratio and stress of evaporation substrate is investigated. The evaporation substrate is one of the most important components in a natural cooling system. Through utilizing phase-transition technology, heat dissipation is realized by a natural cooling system. During operation of evaporation substrate, increase in internal gas pressure, caused by the evaporation of working fluid, leads to deformation of evaporation substrate. Therefore, strengthen-columns are introduced to reinforce the evaporation substrate. Both Pro/E simulation outcomes and experimental results based on structure optimization of evaporation substrate indicate that the optimal design is achieved at a welding area ratio of 1.844%, namely the arrangement of strengthen-columns is 11 × 14 × 3 mm. With this arrangement, the minimum stress on welding surfaces of strengthen-columns and minimum deformation of the evaporation substrate are achieved, which can meet the engineering requirement.

1. Introduction

In recent years, rapid development of power electronic technology to integration and miniaturization requires the high reliability, high flexibility, compact, easy maintaining, and high heat dissipation efficiency of power electronic equipment. Among them, effective cooling methods are the essential method to ensure normal operation of power electronic equipment [1]. Natural cooling method depends on heat convection and heat radiation, making it has many advantages, such as maintenance-free, long service life, high reliability, low cost, no noise, and so on, when compared with forced-air cooling method and water cooling method. Natural cooling method relies on heat pipes cooling technique, which utilize phase-transition and gravity to complete the cycling of working fluid in heat pipes. During one heat dissipation cycle period, heat will be dissipated by flowing working fluid, which ensures the equipment operating under the junction temperature.

In the natural cooling system, the capillary loop is an efficient two-phase heat transfer component, which uses the phase-transition process of working fluid to conduct heat in closed pipes [2-5]. Unlike ordinary heat pipes, the fluid and gas are separated and the capillary structure exists only in evaporator to provide power. The advantages of capillary loop include long transmission distance, high heat power,
high heat conductivity, high temperature uniformity, high reliability, easily controlled, convenient arrangement, etc. Both evaporators and condensers with capillary loop can be parallel connected and operating, making it more flexibility compared with traditional heat pipes. These advantages are helpful to realize the separation of heat source and heat dissipation in power electronic equipment, maintenance-free, and temperature uniformity of equipment. Recently, researchers have experimentally studied the natural cooling system with temperature uniformity property [6]. The results show that through a set of natural cooling system (735 mm × 395 mm × 100 mm), a heat power more than 500 W as well as a heat conduction distance of 3 m are achieved, which meet the requirement of outdoor heat dissipation.

The low-voltage distribution static synchronous compensator (DSTATCOM) device is very important and commonly used at the end of electrical power distribution networks. The currently cooling method for DSTATCOM devices is forced-air cooling and natural cooling method is rarely used. In this work, a natural cooling system is designed to overcome the disadvantages of traditional forced-air cooling systems and to be applied to DSTATCOM devices. The natural cooling system can reduce the noise of low-voltage DSTATCOM and provide maintenance-free operating conditions. Structure optimization based on Pro/E simulation is conducted to achieve heat dissipation at kilowatt level, to reduce the stress and deformation of evaporation substrate, and to meet the engineering requirements.

2. Structure optimization and discussions

2.1. Heat dissipation level

It is known that IGBT is the heat source of low-voltage DSTATCOM devices. Most of DSTATCOM devices adopt three-level topology, as shown in Fig. 1a. The IGBT used in DSTATCOM of this work is Infineon F3L150R07W2E3_B11. According to the parameters provided by the datasheet of IGBT, the heat loss of one IGBT module during operation can be calculated and the corresponding results are listed in Table 1. The specific calculation formulas are referred to the references [7-9]. Since the DSTATCOM consists of six IGBT modules as shown in the topology of DSTATCOM, the total heat loss of DSTATCOM is 1946.628 W. Currently, the largest capacity of single low-voltage DSTATCOM device in industrial fields is 100 kvar. Notably, the objective equipment has a capacity of 200 kvar, which is under designing and requires two DSTATCOM devices operating together. Therefore, the whole heat loss is ~3.9 kW, which means that the heat dissipation requirement of this equipment is at kilowatt level.

Figure 1. (a) Three-level topology diagram of DSTATCOM, (b) the natural cooling system diagram.
Table 1. Heat loss of one IGBT module

| Element | Loss (W) |
|---------|----------|
| IGBT1   | 34.798   |
| IGBT4   | 34.798   |
| XL1     | 19.966   |
| XL4     | 19.966   |
| IGBT2   | 61.909   |
| IGBT3   | 61.909   |
| XL2     | 8.756    |
| XL3     | 8.756    |
| OW1     | 36.79    |
| OW2     | 36.79    |
| Total loss | 324.438 |

2.2. Internal gas pressure of evaporation substrate

Natural cooling system is designed as a gravity-driven and phase-transition coupled natural convection cooling system. It consists evaporation section, adiabatic section, and condensation section, as shown in Fig. 1b. During one heat dissipation cycle period, working fluid in pipeline is vaporized by heat source and transformed into gaseous phase, and moves upward rapidly to condensation section. Thereafter, heat exchange occurs between working fluid and cold source outside the pipes, so that working fluid is condensed and transformed into liquid phase again, returns to evaporation section driven by gravity, and absorbs heat again. In this way, the heat is transferred from the evaporation section to condensation section.

In this natural cooling system, evaporation substrate, which is fixed with heat source, is the core component. Inspired by capillary loops, capillary grooves are introduced to improve the vaporizing efficiency of working fluid during heat absorption process in this work. The growth of gas pressure derived from working fluid evaporation can lead to high stress on welding surfaces of strengthen-columns and deformation of evaporation substrate. To protect the evaporate substrate from excessive stress and deformation damage, a special Cu evaporation substrate with strengthen-columns is machined. The strengthen-columns have a diameter of 3 mm, and a cover plate is welded with strengthen-columns to make a reliable connection between them. The parameters of the Cu evaporation substrate used in this work are listed in Table 2. The size of heat source is 56.7 mm × 48 mm (Infineon F3L150R07W2E3_B11). According to heat simulation with ANSYS Fluent, the average internal temperature of evaporation substrate is ~330 K (~57 ℃) under the rated operating conditions (3.9 kW), as shown in Fig. 2. Combined with the physical properties of working fluid R245fa, it can be known that the internal gas pressure of evaporation substrate is 0.4242 MPa under the rated operating conditions.

Table 2. The parameters of designed Cu evaporation substrate

| Parameters     | Value (mm) |
|----------------|------------|
| Substrate length | 302        |
| Substrate width  | 202        |
| Substrate thickness | 8          |
| Groove width     | 0.5        |
| Groove height    | 1.5        |
| Wall thickness   | 1.5        |
2.3. Structure optimization of the Cu evaporation substrate

The stress on welding surfaces of strengthen-columns and deformation of the used Cu evaporation substrate are analyzed with Pro/E and the structure of strengthen-column is optimized accordingly. According to above calculation result, a gas pressure of 0.5 MPa is used as input pressure for simulation. Fig. 3 is the corresponding results of strengthen-columns with various parameters. Take Fig. 3a as an example, the arrangement of strengthen-columns is 5 lines and 7 rows, and the diameter of one strengthen-column is 3 mm, denoted as 5 × 7 × 3 mm. In this arrangement, the simulation results are shown in Fig. 3a. The welding area of strengthen-columns is 247.275 mm\(^2\), and internal surface area of evaporation substrate is 59004 mm\(^2\), resulting in the welding area ratio of 0.419%. In Fig. 3b, the diameter of strengthen-columns increases from 3 to 5 mm, and the arrangement is 5 × 7 × 5 mm. In this arrangement, the welding area of strengthen-columns is 686.875 mm\(^2\), and internal surface area of evaporation substrate is 59004 mm\(^2\), resulting in the welding area ratio of 1.164%. In Fig. 3c, the arrangement of strengthen-columns is 11 × 12 × 3 mm. In this arrangement, the welding area of strengthen-columns is 932.58 mm\(^2\), and internal surface area of evaporation substrate is 59004 mm\(^2\), resulting in the welding area ratio of 1.58%. In Fig. 3d, the arrangement of strengthen-columns is 11 × 12 × 5 mm. In this arrangement, the welding area of strengthen-columns is 2590.5 mm\(^2\), and internal surface area of evaporation substrate is 59004 mm\(^2\), resulting in the welding area ratio of 4.39%. In Fig. 3e, the arrangement of strengthen-columns is 11 × 14 × 3 mm. In this arrangement, the welding area of strengthen-columns is 1088.01 mm\(^2\), and internal surface area of evaporation substrate is 59004 mm\(^2\), resulting in the welding area ratio of 1.844%.

The results of stress on welding surfaces and deformation of evaporation substrate are shown in Fig. 3f. When the welding ratio is very small (0.419%), the stress on welding surfaces is ~703.8 MPa and deformation of evaporation substrate is achieved as 1.13E-1 mm\(^2\), which obviously cannot meet the normal operating requirements. With the increase in welding area ratio, both the stress and deformation reduce greatly. When the welding area ratio is 1.844%, the minimum stress value on welding surfaces of the strengthen-column and the minimum deformation of evaporation substrate are achieved, which are ~200 MPa and ~1.08E-2 mm\(^2\), respectively. With further increase in welding area ratio, the stress on welding surfaces decreases slightly and the deformation of evaporation substrate increases greatly. These results indicate the optimal welding area ratio of strengthen-columns is 1.844%.
Figure 3. Simulation results of strengthen-columns with various arrangements, (a) 5 × 7 × 3 mm, (b) 5 × 7 × 5 mm, (c) 11 × 12 × 3 mm, (d) 11 × 12 × 5 mm, (e) 11 × 14 × 3 mm; (f) stress on welding surfaces and deformation of evaporation substrate at various welding area ratios, the data are achieved from figures (a)-(e). For each figure, stress and deformation results are presented on the left and right, respectively.

A pressure experiment is conducted to verify the simulation results. The selected arrangement of strengthen-columns is 5 × 7 × 3 mm and 11 × 14 × 3 mm, with welding area ratios of 0.419% and 1.844%, respectively. Nitrogen is used to provide gas pressure ranging from 0 to 0.6 MPa. The result shows that obvious deformation of evaporation substrate occurs at the ratio of 0.419%, as shown in Fig. 4a; and in fact, the deformation starts at 0.3 MPa, which is even lower than the gas pressure under rated operating conditions (0.4242 MPa). This means the welding area ratio of 0.419% cannot meet the requirements at all. Meanwhile, at the welding area ratio of 1.844%, no obvious deformation can be observed on the evaporation substrate even at a pressure of 0.6 MPa, as shown in Fig. 4b. The experimental results are in well agreement with simulation results and indicate the evaporation substrate with the arrangement of strengthen-columns (11 × 14 × 3 mm) can be applied to the natural cooling system for DSTATOM devices.

Figure 4. The Cu evaporation substrate (a) with obvious deformation when its strengthen-column has an arrangement of 5 × 7 × 3 mm and 0.419% welding area ratio, (b) with no obvious deformation when its strengthen-column has an arrangement of 11 × 14 × 3 mm and 1.844% welding area ratio.

3. Conclusion
Based on Pro/E simulation, structure optimization of evaporation substrate is conducted. Through introducing strengthen-columns, evaporation substrate is reinforced. The simulation results show that the optimal design is achieved at a welding area ratio of 1.844%, namely the arrangement of strengthen-columns is 11 × 14 × 3 mm. At this ratio, minimum stress on welding surfaces of strengthen-columns
and minimum deformation of evaporation substrate are achieved. Further, pressure experiment is conducted and the corresponding results are in good consistent with simulation results, indicating the designed structure of evaporation substrate meets the engineering requirement of natural cooling system. This evaporation substrate has great potential for the application in the natural cooling system of DSTATCOM devices, which has a high capacity of 200 kvar.

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