Novel Spray Cooling Plate for Thermal Control of Active Phased Array Radar

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Abstract. Based on spray cooling technology, a new high-integrated subarray cooling plate with multi-nozzles is presented for thermal control of active phased array radar (APAR) with high heat flux density. Firstly, by building a three-dimensional heat transfer and flow model, the simulation work was performed to evaluate both thermal control performance of presented cooling plate for APAR. Then, a special experimental thermal control system for the new cooling plate was established to investigate the thermal performance of presented cooling plate under both static state and vibrative state are investigated. The results showed that the nozzles in the cooling plate got high uniformity in pray characteristics. And by using the new cooling plate, the temperature rise of heat source could be controlled below 43℃ with heat flux density of 323.3 W/cm². Also, the temperature rise of heat source under vibrant state was lower than the static state.

1. Introduction
Active phased array radar (APAR) is the prime example of electronic system, which consists of number of active components and electronic equipment, such as: microwave power transistor, Large scale integrated chips, application specific integrated circuits, high power integrated circuit chips and so on [1-2]. With the rapid development of microelectronics technology, the miniaturization and integration of the APAR have been continuously improved, causing to larger increase of assembly density, power consumption and thermal load of the power component [3-4]. Especially, it is reported that heat flux of high-speed processors and the high-power amplifiers used in APAR can rise to more than 300W/cm² [5-6]. Consequently, well-designed active component can break down and fail over long-time overheating and uneven thermal stress [7].

The heat dissipation technologies for APAR mainly included natural convention cooling, forced convection cooling, phase change cooling, semiconductor cooling, and so on [8-11]. The select of cooling method depends on the heat flux density of high-power amplifiers used in APAR, and as to conventional lower heat flux density, natural cooling and air cooling were usually used. For the higher heat flux density, liquid cooling and evaporate cooling were always selected. Spray cooling is
characterized with higher heat transfer coefficient, which showed advantage in higher heat dissipation rate, small temperature change during cooling, and it was successfully used in the electronic chip cooling of Cray X1/SV2 supercomputer and spacecraft [9-13]. Consequently, spray cooling technology attracted more attentions in thermal control for electronic equipment at recent years [14-15], and it will be a significantly potential method to resolve the high heat flux problems in APAR.

Based on spray cooling technology, this paper proposed a novel high integrated multi-nozzle spray cooling system for thermal control of APAR, and a new experiment was built to investigate the cooling performance of the proposed spray cooling system under both static and vibration state.

2. Integrated thermal design by spray-cooling cold plate

The characteristic of high-frequency APAR such as X-band is with high integration, high heat flux and compact structure whose thermal control should be used thermal integration design method to realize the structure installation and heat dissipation in limited space. Figure 1 gave the schematic diagram of APAR, mainly including radiation units, subarrays, integrated networks, array framework, integrated modules and other components.

The subarray mainly includes support plate and high-power Transmit/receive (T/R) module, in which T/R module is the main heating components of the antenna. Multiple nozzles for spray cooling were installed at the support plate forming a spray cold plate, used to cool the T/R module. The spray cold plate and subarray of nozzles were shown in Fig. 1(b) and Fig. 1(c), including cavity, pipe joint, nozzle and other parts. The cooling fluid enters the static pressure chamber through the inlet, cools the heating surface by spray of nozzle, and then flows back to the main pipe through the outlet.

(a) Antenna array  (b) Integrated subarray  (c) Nozzle atomization

Figure 1. Schematic diagram of the high integrated thermal design of APAR.

There are four slots on the front and the back of the spray cold plate for placing the T/R modules. The working fluid for spray is pumped into the nozzles which is designed at the top of cold plate, out from the nozzle, the working fluids is sprayed to the surface of the T/R module and cool it, and then the hot fluid flows out from the drain port at the bottom of the cold plate. As shown in Fig. 2, the T/R module has 4 channels and each channel has a high-power chip, so 16 nozzles are arranged side by side on the spray cold plate.

Figure 2. Photograph of spray cooling cold plate.
3. Simulation of the spray cold plate
A mathematical model was set up by ANSYS/FLUENT to simulate the flow and heat transfer of spray cold plate during the spray cooling. Firstly, the spray cold plate was processed as follows: the inlet pipe and nozzle entity were cleared, removing the chamfering, fasteners and bolts. The simulation model with a total mesh number of about 2 million was shown in Fig. 3.

![Figure 3. Simulation model of the spray cold plate.](image)

The standard k-turbulent model was adopted and discrete phase model was used to simulate the spraying process, taking into account the impact/crushing/evaporation of droplets. The interaction between the liquid film and the surrounding air was also considered. As shown in Fig. 4, the liquid film gradually formed and flow downward along the wall to the bottom, then aggregate and flow out of the outlet, eventually forming a continuous liquid film. And the spray characteristics of the four nozzles array are almost consistent with little mutual interference, indicating that the design of nozzle array design is reasonable.

![Figure 4. Evaluation results of spray cooling cold plate.](image)

4. Experiment of novel spray cold plate
In order to investigate the heat transfer characteristic of multiple-nozzles spray cold plate, a special experiment was designed.

4.1. Experiment system
As shown in Fig. 5(a), the experiment system includes liquid pump, buffer, flow meter, spray cold plate, condenser, reservoir, filter, and temperature and pressure measuring equipment and a data acquisition instrument. In order to simulate high heat flux, the thick film resistors were manufactured as heat source equal to heat flux from chip. The resistors were assembled into the T/R modules enclosure through high-temperature welding, as shown in Fig. 5(b).
With glycol aqueous solution as the working fluid, the experiment was carried out and the conditions are shown in Table 1.

### Table 1. Experiment conditions.

| Parameters                     | Value | Parameters                     | Value |
|--------------------------------|-------|--------------------------------|-------|
| Room temperature (°C)          | 18.0  | Spray flow rate (L/h)          | 3.5–5.0 |
| Spray angle (°)                | 35    | Radius of nozzle (mm)          | 0.3   |
| Spray pressure (bar)           | 4–6   | Condenser water temperature (°C) | 22–26 |

#### 4.2. Results of experiment

The built spray cooling experimental system was used to test the new cold plate, both the cold plate at static and vibration state were tested respectively at room temperature and pressure. It can be found that after electrification, the chip temperature rapidly increases, and tends to be constant at 50s, then reaches the equilibrium temperature at 100s. As shown in Fig. 6, the larger the heat flux density and the higher equilibrium temperature. The maximum heat flux for the array 323.3 W/cm², and the temperature rise is 43 °C.

![Figure 5](image1.png)  
**Figure 5.** Experiment system of the novel cold plate

![Figure 6](image2.png)  
**Figure 6.** Heat resource temperature change with heat flux

In order to verify the effect of spray on cold plate, both the cold plate with and without nozzle were test, the temperature rise and temperature uniformity for heat sources were shown in Fig. 6(b) and Fig. 6(c), respectively. The maximum temperature difference represented the maximum temperature difference between the four heat sources, characterizing the temperature uniformity of cold plate. Experimental results showed that with nozzles spray the temperature of heat source increased to 35 °C at heat flux 275 W/cm², but the temperature could rise to 90 °C for cold plate without nozzles spray. Also, temperature difference between the four heat sources was about 5 °C with spray cooling, but
13 °C without spray cooling. Consequently, by the nozzle spray, temperature rise and temperature non-uniformity could be significantly reduced.

Since the APAR works always at moving and vibrant state, the thermal control performance of the presented spray cold plate should be specified under vibration. The vibration test platform and conditions are shown in Fig. 7. The experimental results show that under random vibration, the cold plate temperature rise is more than that under static state, and the maximum rise rate is 7.6% with the same heat flux of the heating power.

![Vibration test platform](image1)

![Vibration test condition](image2)

![Vibration test result](image3)

**Figure 7.** Vibration test of spray cold plate.

### 5. Conclusion

Aiming to the characteristics of high integrated and large heat flux APAR, a new type of subarray spray cold plate with integrated thermal control structure was proposed, the structure integration, nozzle performance and spray cooling performance were designed and simulated, and the special spray cooling experimental system was built to investigate the thermal performance of the new cold plate. Results show that the integration of subarray sample spray performance is good, the heat dissipation ability can reach to heat flux density of 323.3 W/cm², the temperature rise for 43 °C, with a high in-homogeneity temperature. The cold plate showed better performance under vibrant state than that under static state. Consequently, the new spray cold plate can be effectively applied to thermal control of the APAR with high heat flux and high temperature consistency.

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