High power density thermal control design of onboard phased array antenna

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Abstract. Thermal control of high power density phased array antenna [1] has become a critical problem for onboard seeker which is confined by compact structure and harsh flight condition [2-4], different from land-based or airborne seekers. As a key technology, thermal control of onboard phased array antenna faces the challenge of high density power element as well as worse operating temperature. Using finite volume method as theoretic foundation of numerical simulation, this paper firstly calculates temperature field and fluid field via discrete control equation group, which is transformed from continuous integration equation group according to energy reservation equation. Next, 2 kinds of phased array antenna with phase change energy storage and water cooling are designed and evaluated by thermal control performance simulation. Then advice is given for reasonable assembly after temperature distribution of phased array antenna is quantified under different assembly state with the influence of contact thermal resistance. At the end, precision of temperature simulation is verified with temperature test result of phased array antenna.

Keywords: phased array antenna, thermal control, contact thermal resistance

1. Foreword
Thermal control problem rises along with popular application of onboard phased array antenna, which takes nearly 80%~85% [5] thermal power consumption of the seeker with thousands of compact arranged T/R units on antenna aperture. Antenna temperature will rise endlessly if heat generated by power element can not be quickly dissipated out under condition of small space and large heat flux density. Then, T/R units will go bad or failure, which deteriorates antenna electric performance. So thermal control design of phased array antenna directly influence detection capability of active phased array antenna, for which normal operation of thousands of T/R units should be guaranteed during the flight.

According to relative documents [6], about 55% failure of electronic equipment is brought by outrange temperature of electronic components, whose operating reliability is especially sensitive and exponentially decreased with the rising of temperature. Lifetime and reliability of electronic component will be greatly degraded when temperature cyclic change exceeds ±15℃. Failure rate can increase to 8.1 time when temperature cyclic change exceeds ±20℃. Therefore, thermal control technology research is necessary for onboard active phased array antenna. Finite volume method is adopted in this paper for thermal control design to give full play to the advantages of phased antenna.
2. Theoretical basis
Finite volume method is adopted in this paper to calculate temperature field of phased array antenna as well as fluid field distribution of water cooling system. At first, calculated region is divided into a serial of unrepeated control volume, which embrace mesh node one by one [7]. Then according to energy reservation principle, differential equation to be solved is integrated for each control volume to obtain a group of discrete equations, which are finally solved to get physical parameters like temperature, flow velocity, concentration and etc. The followings are some theoretical formulas [8], which are already deduced and widely used by predecessors.

\[ w \delta P = \frac{\rho c}{\delta t} \int_w^{t+\Delta t} \left( \frac{\partial T}{\partial t} \right)_w \, dt \, dV - \int_w^{t+\Delta t} \left( kA \frac{\partial T}{\partial t} \right)_e \, dt + \int_w^{t+\Delta t} \bar{S} \Delta V \, dt \]  

Here, \( A \) represents the area of control volume, \( \Delta V \) represents the volume. \( \Delta V = A \Delta x \), \( \Delta x \) represents the width of control volume. \( \bar{S} \) represents the average \( T \) intensity of control volume. Temperature of point \( P \) at time point of \( t \) is set as \( T_P \), while temperature of point \( P \) at time point of \( t+\Delta t \) is set as \( T_{Pe} \). To calculate \( T_P \), \( T_E \) and \( T_W \) are integrated along time with a weight factor \( \theta = 0-1 \). So equation (1) is changed as below after discretion:

\[ \rho c \left( \frac{T_P - T_{Pe}}{\Delta t} \right) \Delta x = \theta \left[ \frac{k_u(T_P - T_E)}{\delta x_{Pe}} \right] + \left( 1 + \theta \right) \left[ \frac{k_u(T_E - T_W)}{\delta x_{Pe}} \right] + S \Delta x \]  

In the above equation, initial temperature as well as \( T_P \), \( T_E \) and \( T_W \) at time point of \( t \) are already known. So, it shows the relationship between \( T_P \), \( T_E \), \( T_W \) at time point of \( t+\Delta t \). Linear algebraic equation group for all unknown parameters call be obtained after above equation is listed for 3 adjacent nodes in calculated region. Linear algebraic equation group can be solved after boundary condition is given.

3. Thermal control design of phased array antenna
Shown as fig.2, the antenna includes 2 kinds of T/R units and one cooling board. It has 128 channels. Under high-power state, overall power is 1408W with single channel power of 11W. Under low-power state, overall power is 74.24W with single channel power of 0.58W. Cooling board operates in 2 modes, i.e. phase change energy storage mode and water cooling mode. 80# paraffin is used as phase change material.
3.1. Design of phase change energy storage
Phase change material is filled into cooling board for phase change energy storage operating mode. This simulation choose 80# paraffin, whose phase changes at 80°C. Calculation result is give as below with antenna initial temperature of 70°C.

According to fig.3, it can be known as followings:
(1) With initial temperature of 70°C, chip is the hottest part of phased array antenna with maximal temperature of 97°C. So heat of T/R element goes quickly to cooling board when vapor chamber has high conduction coefficient.
(2) Temperature at Central region of cooling board rises to and stay at 80°C after 15s. From then on, phase of paraffin inside cooling board changes and heat generated by T/R element is greatly absorbed. Therefore, the temperature rising of chip is staggered until 22s, i.e. the end of phase change occurred inside cooling board.
(3) Temperature of antenna aperture rises slowly because of the long distance between aperture and T/R units as well as the heat isolation brought by cooling board.

3.2. Design of water cooling
Water cooling [9-11] is usually used during laboratory adjustment of phased array antenna to insure long time operating of antenna. Temperature simulation is done for phased array antenna under water cooling condition [12-13]. Temperature curves of central chip, cooling board and water outlet are given at the end.
Initial temperature of antenna is 25°C. Water cooling is used. Overall power is 1408W with single channel power of 11W. Flow speed of cooling water is 5L/min. Flow channel is designed as 11 parallel channels with same width. Temperature calculation result is given as below.

**Figure 4.** Flow channel model for phased array antenna

**Figure 5.** Temperature distribution phased array antenna in water cooling mode

(a) antenna temperature distribution at 100s   (b) antenna temperature distribution at 200s

**Figure 6.** Temperature curve of phase array antenna
According to fig.5 and fig.6, it can be known that chip temperature of phased array antenna is quickly balanced under water cooling operating mode with maximum value of 78.1 ℃ at 300s. To guarantee long time stable operation, water cooling is better than phase change energy storage, which can only promise short time stable operation of phased array antenna.

4. Influence of contact thermal resistance

To prevent chips from being burnt, heat generated by high-power chips of phased array antenna should be quickly conducted to cooling board despite of extreme bad operating condition brought by compact volume, complicate structure and high flux density. The whole heat conduction process uses interface contact between thin aluminum boards, where contact gaps filled by air brings bad contact and large thermal resistance [14]. Shown as Fig.7, silicon grease is usually used to fill the gap, increase contact area and heat conduction capability. High performance heat conduction silicon grease made by 5thacademy of CASC can reduce contact thermal resistance to 5mm²K/W by now.

Figure 7. Chart of contact thermal resistance and filled heat conduction silicon grease

As a key factor, interface contact pressure influences contact thermal resistance by changing real contact area between solid-solid interfaces. Laboratory test of contact thermal resistance is done by Nanjing University of science and technology under different pressure for aluminum boards with different coarseness [15]. Result is given in Fig.8.

Figure 8. Curve of contact thermal resistance via interface pressure for dry contact of aluminum boards

Temperature response of phased array antenna is calculated with different contact thermal resistance among T/R assembly, vapor chamber and cooling board for 3 kinds of assembly states as below:
(1) Dry contact without tight compression, whose Contact thermal resistance is 300 mm²K/W;
(2) Dry contact with tight compression, whose Contact thermal resistance is 50 mm²K/W;
(3) Gaps filled with Heat conduction silicon grease, whose Contact thermal resistance is 5 mm²K/W. Result is given in Table 1.

**Table 1.** Chip temperature under different assembly state of T/R assembly

| Numble                        | Dry contact without tight compression | Dry contact with tight compression | Gaps filled with Heat conduction silicon grease |
|-------------------------------|--------------------------------------|----------------------------------|-----------------------------------------------|
| Contact thermal resistance    | 300 mm²K/W                           | 50 mm²K/W                        | 5 mm²K/W                                      |
| Chip temperature              | 155 ºC                               | 135 ºC                           | 126 ºC                                        |
| Central temperature of cooling board | 96 ºC                               | 105 ºC                           | 109 ºC                                        |

According to Table 1, when contact thermal resistance grows larger, heat conduction from chips to cooling board becomes harder as well as chip temperature rises. So contact interfaces among T/R assembly, vapor chamber and cooling board should be filled with heat conduction silicon grease and compressed as tight as possible during the assembly of phased array antenna to decrease chip temperature.

5. **verification test**

Performance test in dark room is done on a phased array antenna, which is cooled by phase change energy storage and installed with thermocouple for real-time temperature measurement under ambient temperature of 25 ºC. Temperature test result is compared with corresponding simulation result and shown as Fig. 9.

![Figure 9. Thermal control result comparison between test and simulation of phased array antenna](image)

According to the comparison above, test and simulation temperature rise curves of chip fit well with each other despite those of cooling board deviate from each other within certain degree.

Compared with test result of 43.9 ºC, simulation temperature of cooling board is 47.5 ºC at 50s with a relative difference of 8.2%, whose reason is analyzed as contact thermal resistance and heat dissipation brought by the long distance between cooling board and heat source.
6. Conclusion
Thermal control methods like Phase change energy storage and water cooling are designed in this paper for urgent need of onboard phased array antenna. Finite volume method is adopted for temperature and fluid simulation on two kinds of antennas. Influence of contact thermal resistance on temperature of antenna chip and cooling board is quantized via temperature simulation under different assembly state and verified by comparison with test temperature. Chip temperature enjoys higher precision while cooling board bears lower precision with 8.2% tolerance between test and simulation.

References
[1] WANG C S, BAO H, ZHANG F S, FENG X G. Analysis of electrical performances of planar active phased array antennas with distorted array plane [J]. Journal of Systems Engineering and Electronics, 2009, 20(4): 726-731.
[2] WANG C S, DUAN B Y. Coupled structural electromagnetic thermal modeling and analysis of active phased array antennas [J]. IET Microwaves, Antennas & Propagation, 2010, 4(2): 247-257.
[3] WANG C S, DUAN B Y. Analysis of performance of active phased array antennas with distorted plane error [J]. International Journal of Electronics, 2009, 96(5): 549-559.
[4] WANG C S, DUAN B Y. On distorted surface analysis and multidisciplinary structural optimization of large reflector antennas [J]. Int. J. Structural and Multidisciplinary Optimization, 2007, 33(6): 519-528.
[5] Chen S F, Wang C S. Design and fluid-thermal coupling analysis of onboard active phased array antenna cooling board, Xidian university, 2012.
[6] Qian J F, Zhang Y F. Thermal analysis based discussion on reliability of electronic components [J]. Information of micro computer, 2005, 21(32): 161-163.
[7] Tan W Y. Application of FVM in shallow water dynamics calculation [M]. Beijing: Tsinghua university press, 1998.
[8] Bin X, Peng J, Feng X A Multi—Moment Finite Volume Method forIncompressible NaVier—Stokes Equationson Unstructured Grids, ACTAAERODYNAMICA SINICA, 2016.4.
[9] LI J, PETERSON G P, CHENG P. Three- dimensional analysis of heat transfer in a micro-heat sink with single phase flow [J], Int. J. Heat Mass Transfer 2004, 47: 4215 – 4231.
[10] HUSAIN A, KIM K Y. Design optimization of microchannel for microelectronic cooling [C] // The Fifth International Conference on Nanochannels, Microchannels and Minichannels, Puebla, Mexico, 2007: ICNMM 2007-30053.
[11] GAMRAT G, FAVRE M M, LE P S. Modelling of Roughness Effects on Heat Transfer in Thermally Fully-Developed Laminar Flows Through Microchannels [J]. International Journal of Thermal Sciences, 2009, 48(2009): 2203-2214.
[12] Toh K C, CHEN X Y, CHAI J C. Numerical computation of fluid flow and heat transfer in microchannels [J], Int. J. Heat Mass Transfer 2002, (45): 5133–5141.
[13] ANTONIO F. Constructural branching design for fluid flow and heat transfer [J]. International Journal of Heat and Mass Transfer, 2018, 122: 204-211.
[14] Lee WS, Yu J. Comparative study of thermally conductive fillers in underfill for the electronic components [J]. Diam Relate Mater 2005, 14(10): 1647—53.
[15] Qi N, Han Y G. Laboratory research on Solid-solid interface contact thermal resistance and development of databasequery system, Nanjing University of science and technology, 2013.