Air-cooled Design of 4 kW DC Bus Converter on Airplane

Kaichang Xue 1, 2, a and Zongxin Luo 1, 2, b

1 The 0616-research institution of Guizhou Aerospace Linquan Motor Co., Ltd., Guizhou 550081, China
2 National Engineering Research Center for Small and Special Precision Motors, Guizhou 550081, China

a xuekc@nercsspm.cn, b luozx@nercsspm.cn.

Abstract. To meet the application requirements of 4 kW DC 270 to DC 28 V converter on airplane, an air-cooled design method is proposed. According to converter’s circuit structure, the losses of main components and the air-cooled design structure are determined. The thermal resistance model of the air-cooled is built, and the process of the air-cooled design is illustrated. Then the air pressure and air volume of fan are determined. The results demonstrate that the temperature rise of the heat sink is less than 35°C when the output is 4 kW and the converter can work reliably when ambient temperature is 70°C.

Keywords: converter; aircraft DC bus; air-cooled; high temperature experiment.

Nomenclature

- $A_i$ -- Area of baseplate outside, m$^2$
- $A_o$ -- Total surface area of fins, m$^2$
- $A_v$ -- Cross-sectional area of a fin, m$^2$
- $c_a$ -- Specific heat capacity of air, J/(kg·°C)
- $c_1$ --Stripe coefficient
- $f_{app}$ -- Apparent friction factor
- $h$ -- Heat transfer coefficient, W/(m$^2$·°C)
- $H$ -- Height of fin, m
- $k_a$ -- Thermal conductivity of air, W/(m·°C)
- $k_o$ -- Thermal conductivity of heat sink, W/(m·°C)
- $L$ -- Heat sink length, m
- $L_f$ -- Air circulation length in heat sink, m
- $L_s$ -- Heat source length, m
- $n_f$ -- Fin number of heat sink
- $Nu$ -- Nusselt number, $h_s/k_a$
- $p$ -- Static pressure of fan, Pa
- $p_m$ -- Rate value of the static pressure of fan, Pa
\( \Delta P_a \)-- Total pressure drop, Pa
\( \Delta P_l \)-- Total pressure drop of inlet and outlet, Pa
\( \Delta P_c \)-- Core pressure drop, Pa
\( P \)-- Power, W
\( Q \)-- Volumetric flow rate, m\(^3\)/min
\( Q_m \)-- Rate value of the volumetric flow rate of fan, m\(^3\)/min
\( R_{ba} \)-- Thermal resistance of the baseplate outer surface to the air, °C/W
\( R_{bf} \)-- Thermal resistance of the baseplate, °C/W
\( R_{cb} \)-- Thermal resistance of heat source to the baseplate outer surface, °C/W
\( R_{fa} \)-- Thermal resistance of fins to the air, °C/W
\( Re \)-- Reynolds number, \( V_\text{as} / \nu \)
\( s \)-- Fin spacing, m
\( t_a \)-- Fin thickness in root, m
\( t_b \)-- Baseplate thickness, m
\( T \)-- Temperature, °C
\( T_a \)-- Air temperature, °C
\( T_b \)-- The outer surface temperature of baseplate, °C
\( T_f \)-- The inner surface temperature of baseplate, °C
\( T_i \)-- The temperature of the heat source, °C
\( \Delta T_a \)-- The temperature rise of air, °C
\( \Delta T_s \)-- The temperature rise of heat sink, °C
\( V_a \)-- Average velocity in fin channel, m/s
\( V_{a1} \)-- Inlet and outlet velocity of heat sink, m/s
\( V_{\text{max}} \)-- Maximum velocity in fin channel, m/s
\( W \)-- Heat sink width, m
\( W_s \)-- Heat source width, m

Greek Symbols
\( \rho_a \)-- Air density, kg/m\(^3\)
\( \eta_f \)-- Fin efficiency
\( \varepsilon \)-- Contraction ratio
\( \nu \)-- Kinematic viscosity, m\(^2\)/s

1. Introduction
Compared with constant-voltage constant-frequency AC power supply and constant-voltage variable-frequency AC power supply, 270V high-voltage DC power supply has higher efficiency, and its power generation and distribution equipments are smaller for high power aircraft power supply.[1] 270V high-voltage DC power supply has been one of the main development trends. Meanwhile, on-board equipment still has a certain requirement for 28V low-voltage DC power. Therefore, DC 270V to DC 28V converter is a crucial equipment.

In this paper, the application background of the air-cooled design is a DC 270V to DC 28V converter, which works in 100kHz and has 4kW output power. An air-cooled heat dissipation structure adopting centrifugal fan and heat sink with striped fins is proposed. The calculation process of fan air volume and air pressure is presented. Finally, the air-cooled design is verified by experimental results.

2. Losses of Converter
The simplified circuit of DC 270 V to DC 28V converter is shown in Fig 1. Capacitance \( C_i \) is used to smooth input voltage \( V_i \). Transistors \( V_1 \) to \( V_4 \) compose the full-bridge, which is used to convert 270V input DC \( V_i \) into 100 kHz high-frequency AC \( v_1 \). Transformer T is used to realize the initial adjustment.
of input and output voltage, the isolation of input and output, and the output of high-frequency AC \( v_2 \). Diodes \( D_1, D_2 \) and inductances \( L_1, L_2 \) compose the high-frequency rectifier, which converts high-frequency AC \( v_2 \) into output DC \( V_o \). Capacitor \( C_b \) is used to suppress the DC magnetic bias of transformer. An auxiliary circuit consisting of inductance \( L_r \) and diodes \( D_{a1}, D_{a2} \) is used to suppress the peak of reverse voltage on rectifier diodes \( D_1, D_2 \). This converter adopts phase-shift full-bridge control. Capacitors \( C_1-C_4 \) in parallel with transistors \( V_1-V_4 \) respectively are used to realize soft switching of transistors. Inductance \( L_r \) is also beneficial to make lagging bridge arms consisting of \( V_3 \) and \( V_4 \) achieve soft turn-off easier. The control circuit detects the output voltage \( V_o \), and adjusts the phase shift angle of the primary bridge to keep output voltage \( V_o \) in desired value. The main components of the converter are shown in Table 1. The main component losses of the converter are shown in Table 2.

The conduction loss of each transistor in \( V_1-V_4 \) is 25W, and the switching loss is 20W. The windings ratio of transformer \( T \) is 6:2. The transformer adopts two PEE64 magnetic cores. The iron loss and copper loss of transformer \( T \) are 7W and 12W respectively. Inductance \( L_r \) adopts a PEI58 magnetic core, and the number of turns is 2. The iron loss and copper loss are 2.1 W and 1.4 W respectively. Any one of the inductances \( L_1, L_2 \) adopts a PEE64 core. The number of turns is 2. The iron loss and copper loss are 1W and 8W respectively.

![Fig.1 Simplified circuit of the DC 270 V - DC 28V converter](image)

| Table 1 Main components of converter |
|-------------------------------------|
| \( V_1-V_4 \) | \( C_i \) | \( C_1-C_4 \) | \( C_b \) | \( T \) |
| APT40GP60JDQ2 | 22 \( \mu \)F | 7.5 nF | 33 \( \mu \)F | 6:2 |
| \( D_{11}, D_{22} \) | \( L_1, L_2 \) | \( L_r \) | \( C_o \) | \( D_{a1}+D_{a2} \) |
| 4\times(DSS2×101-02A) | 4.5 \( \mu \)H | 2.3 \( \mu \)H | 6000 \( \mu \)F | DSEI2×30-06C |

The upper limit working temperature of power semiconductor devices \( V_1-V_4 \) and \( D_1, D_2 \) is 150°C. In order to guarantee its reliability, the temperature of heat sink’s baseplate should be usually less than 110°C. Magnetic elements \( T, L_r, L_1 \) and \( L_2 \) are composed of ferrite material, and its Curie temperature is 240°C. The upper limit working temperature of Magnetic elements’ windings is 180°C. So it is reasonable that the magnetic components work below 150°C. Due to that the upper limit ambient temperature of the converter is 65°C to 70°C, the temperature rise of heat sink’s baseplate should be less than 35°C, and the temperature rise of magnetic components should be less than 70°C.

| Table 2 Main components loss of converter |
|------------------------------------------|
| \( V_1-V_4 \) | \( T \) | \( D_{11}+D_{22} \) | \( L_r \) | \( L_1+L_2 \) |
| 180 W | 19 W | 100 W | 3.5 W | 18 W |

3. Air-cooled structure and analysis model

According to the loss distribution shown in Table 2, the structure of air-cooled heat dissipation is shown in Fig2. Fig2(a) shows the distribution of the main components on the surface of the heat sink. The
dotted line envelope represents the centrifugal fan embedded in the heat sink fins, and the direction of air flow is shown as the arrows. The side view shown in Fig 2(b) is viewed from cross section \( A_1 \). The arrow in Fig 2(b) indicates the air flow direction between the heat sink fins. The air enters the gap between heat sink baseplate and fans in the lower left-side, flows through the fan, and then flows out through the gaps of fins in the upside. The air flow length \( L_f \) is approximately equal to the width of heat sink. The fins at the bottom are truncated to place the fan. The effective heat dissipation area of the lower fins is smaller than that of the upper fins. Therefore, the power semiconductor devices with high loss are mainly arranged in the upper region.

Fig. 2 shows that the primary full-bridge consisting of transistors \( V_1-V_4 \) has the maximum loss and is located in edge of the heat sink. This region is the most severe region of heat dissipation. Therefore, this area is the focus of heat dissipation design in the following analysis.

The thermal resistance model is shown in Fig. 3. \( L_e \) and \( W_e \) represent the equivalent heat source length and width of the primary full-bridge respectively, and \( L \) and \( W \) represent the length and width of the equivalent heat sink respectively. The height and root thickness of the fins are \( H \) and \( t_a \) respectively. The space between the fins is \( s \). \( A_i \) and \( A_o \) are the outside area of the heat sink baseplate and the total surface area of the fins respectively, and the thickness of the baseplate is \( t_b \). In Fig 3(b), \( T_i \), \( T_b \), \( T_f \) and \( T_a \) represent the temperature of the heat source, the outer surface of the baseplate, the inner surface of the baseplate and the air respectively. \( R_{cb} \), \( R_{bf} \), \( R_{fa} \) and \( R_{ba} \) represent the thermal resistance of heat-source to outer surface of baseplate, baseplate, fins to air and outer surface of baseplate to air respectively [2].

![Fig.2 Structure of air-cooled](image-a)

![Fig.3 Thermal resistance model](image-b)

The thermal resistance \( R_{cb} \) is diffusion thermal resistance. Due to that the calculation of \( R_{cb} \) is complicated. 10 °C to 15 °C of temperature loss is allowed to assess the effect of \( R_{cb} \), when heat dissipation power of the devices in unit area is distributed as evenly as possible. The thermal resistance
$R_{ba}$ value of the outer surface of the baseplate to air is large and has little influence on the overall heat dissipation analysis. $R_{ba}$ can be ignored. In engineering applications, the thermal resistance $R_{bf}$ of baseplate and the thermal resistance $R_{fa}$ of fins to air should be mainly considered. The expressions are shown in Eq. (1) and Eq.(2) respectively.

$$R_{bf} = \frac{l}{k_f A_f}$$  

where, $k_f$ is the heat conductivity of the heat sink.

$$R_{fa} = \frac{1}{h A_f \eta_f}$$

where, $h$ is the heat transfer coefficient of heat sink to air, $\eta_f$ is the heat sink efficiency.

### 4. Design process

The design process of air-cooled heat dissipation of the primary full-bridge region includes the following steps. [3,4]

**Step 1)** Losses should be calculated. According to Table 2 and considering the corresponding margin, 240W is chosen as the dissipation power of the full-bridge transistors for the heat dissipation design.

**Step 2)** A heat sink should be selected first. $Nu$ should be calculated with an air velocity, and then the heat transfer coefficient $h$ should be obtained. The heat sink parameters are shown as following. Average fins thickness $t_a=2.5\text{mm}$, fin spacing $s=4.8\text{mm}$, baseplate thickness $t_b=7\text{mm}$, fins height $H=40\text{mm}$, the heat sink’s equivalent width $W=140\text{mm}$, thermal conductivity $k_f=160\text{W}/(\text{m}\cdot\text{°C})$, the heat sink's equivalent length $L=140\text{mm}$, the heat sink's equivalent total surface area $A_o=1.53\text{m}^2$, and fin number $n_f=19$. The heat sink fins has stripes along the direction of air flow to increase the surface area of heat dissipation. The ratio of the surface area of fins with stripes and the surface area of smooth fins is defined as the stripe coefficient $c_1$, and the calculation of $c_1$ is shown as Eq. (3). The calculation result is that $c_1=2.06$.

$$c_1 = A_o/(2n_fLH)$$

Assuming $V_a=5\text{m/s}$, where $V_a$ is average velocity in fin channel. The Reynolds number is shown as Eq.(4).

$$Re = \frac{V_a s}{\nu}$$

where, $\nu$ is kinematic viscosity. The value of $\nu$ is $17\times10^{-6}\text{ m}^2/\text{s}$ when $\nu$ is calculated by air kinematic viscosity in 40°C. The calculation result is that $Re=1412$.

Eq.(4) show that $Re < 2200$. So air flow for air-cooled heat dissipation can be treated as laminar flow[5]. The Nusselt number is shown as Eq.(5).

$$Nu = \left[ 23.4 \left( x^+ \right)^{-3} + \left( x^+ \right)^{-1.28} \right]^{-1/3}$$

where, $x^+ = Re \cdot s/L=48.4$. The calculation result is $Nu=5.18$.

When air temperature is 40°C, the air thermal conductivity is about $2.75\times10^{-2}\text{ W}/(\text{m}\cdot\text{°C})$. So heat transfer coefficient is shown as Eq.(6).

$$h = Nu k_s / s$$
The calculation result is that \( h = 29.7 \text{W/(m}^2 \cdot ^\circ \text{C)} \).

**Step 3)** Fin efficiency should be calculated. When \( h \) is known, the fin efficiency \( \eta_f \) can be got from Fig.4[4]. The heat sink adopt rectangular fin. The horizontal coordinate in Fig.4 is shown as Eq.(7).

\[
\sqrt{c_h/k_i A_i} H^{3/2}
\]  

(7)

where, \( A_i \) is longitudinal cross-sectional area of fins, and \( A_c = t_c H \). The calculation result is 0.49. According to Fig.4, the fins efficiency \( \eta_f = 0.86 \).

**Step 4)** Thermal resistance should be calculated. According to the thermal resistance model, baseplate thermal resistance \( R_{bf} \) and convection thermal resistance \( R_{fa} \) between fins and air are mainly focused. They are shown as Eq.(8) and Eq.(9) respectively. The calculation result are that \( R_{bf} = 2.2 \times 10^{-3} \text{^\circ C/W} \) and \( R_{fa} = 91 \times 10^{-3} \text{^\circ C/W} \).

\[
R_{bf} = t_b/(k_i A_i) = t_b/(k_i WL)
\]

(8)

\[
R_{fa} = 1/(hA_s \eta_i)
\]

(9)

**Step 5)** Pressure drop of the heat sink should be calculated [6,7]. The heat sink’s compactness factor \( \varepsilon = s/(s + t_a) = 0.67, K_v = 0.8 - 0.4 \varepsilon^2 = 0.62, K_v = (1-\varepsilon)^2 - 0.4\varepsilon = -0.12 \). The pressure drop of inlet and outlet is \( \Delta p_i \), Which is shown as Eq. (10). Core pressure drop is \( \Delta p_c \), Which is shown as Eq. (11).

\[
\Delta p_i = (K_v + K_v) \rho_a V_{\text{amax}}^2 / 2 = 0.5 \rho_a V_{\text{amax}}^2 / 2
\]

(10)

where, \( \rho_a \) is air density and its value is 1.13 kg/m\(^3\) at 40°C. \( V_{\text{amax}} \) represents maximum velocity in fin channel. It is approximately equal twice of \( V_a \) for laminar flow.

\[
\Delta p_c = \left[ 4 f_{app} \cdot 2 \Re / \left( 4 x^* \right) \right] \left( \rho_a V_{\text{amax}}^2 / 2 \right) = 1.46 \rho_a V_{\text{amax}}^2 / 2
\]

(11)

where, \( x^* = \Re \cdot s/L_f \) is air circulation length in heat sink and approximately equal to the width of the converter. \( L_f = 235 \text{ mm} \).

\[
2 f_{app} \Re = 23.7366 + 0.219847 \times \left( 4 x^* \right) - 6.43526 \times 10^{-3} \times \left( 4 x^* \right)^{1.5} + 7.39124 \times 10^{-5} \times \left( 4 x^* \right)^2 \]

\[
-3.81290 \times 10^{-9} \times \left( 4 x^* \right)^3
\]

(12)

where, \( f_{app} \) is apparent friction factor.

Total pressure drop is shown as Eq. (13). The calculation result is that \( \Delta p = 117 \text{Pa} \).

\[
\Delta p_a = \Delta p_i + \Delta p_c
\]

(13)

According to the principle of flow conservation, the velocity at the outlet of the heat sink is shown as Eq. (14). The calculation result is that \( V_a = 3.63 \text{m/s} \).
\[ V_{a1} = V_a e \] \hspace{1cm} (14)

![Fig.4 Efficiency curves of striped fins](image)

**Fig.4 Efficiency curves of striped fins**

**Step 6)** Volumetric flow rate and air temperature rise should be calculated. Volumetric flow rate \( Q \) is shown as Eq.\((15)\). The calculation result is that \( Q = 1.22 \text{m}^3/\text{min} \).

\[ Q = 60V_{a1} \times WH \] \hspace{1cm} (15)

The temperature rise of inlet and outlet air is shown as Eq.\((16)\). The calculation result is that \( \Delta T_a = 9.8^\circ \text{C} \).

\[ \Delta T_a = 60P/(\rho_a c_a Q) \] \hspace{1cm} (16)

Where, \( c_a \) is the specific heat capacity of air and its value is 1000 \( \text{J/(kg} \cdot \text{°C)} \).

**Step 7)** The results at different wind velocity should be calculated by Step1) to Step 6). Table 3 shows all the parameter values of \( V_a \) with 0.5 m/s as step. In Table 3, the temperature rise of heat sink is calculated by Eq. \((17)\).

\[ \Delta T_s = P \times (R_{bf} + R_{fa}) \] \hspace{1cm} (17)

where, \( P \) is power, and \( P = 240 \text{ W} \).

According to Table 3, when the wind velocity \( V_a = 5\text{m/s} \), the temperature rise of the heat sink is 22.3\(^\circ\text{C}\), and the thermal resistance of heat sink can meet the requirement of heat dissipation. At this time, the corresponding volumetric flow rate \( Q \) is 1.22\( \text{m}^3/\text{min} \), and static pressure \( \Delta p \) is 117 Pa. Finally, a fan BFB1224GH of 24V/1.6A is selected for the primary full-bridge heat dissipation. The parameters of BFB1224GH are that rated volumetric flow rate \( Q_m \) is 1.71\( \text{m}^3/\text{min} \), rated static pressure \( p_m \) is 1019Pa, and rated power is 38.4W. When the static pressure \( \Delta p = 196\text{Pa} \), the air volume \( Q = 1.4\text{m}^3/\text{min} \), which can be obtained by viewing the fan character curve. It can meet the requirement of heat dissipation.
Table 3 Parameter values in different air velocity

| $V_a$ m/s | 3 | 3.5 | 4 | 4.5 | 5 | 5.5 | 6 |
|-----------|---|-----|---|-----|---|-----|---|
| $x'$      | 29.0 | 33.9 | 38.7 | 43.6 | 48.4 | 53.2 | 58.1 |
| $Nu$      | 4.11 | 4.41 | 4.69 | 4.95 | 5.18 | 5.41 | 5.62 |
| $h$ W/(m·°C) | 23.6 | 25.3 | 26.9 | 28.3 | 29.7 | 31.0 | 32.2 |
| $\eta$ | 0.89 | 0.88 | 0.87 | 0.87 | 0.86 | 0.86 | 0.85 |
| $R_a\times 10^3$ °C/W | 111 | 104 | 99 | 94 | 91 | 87 | 85 |
| $Q$ m³/min | 0.73 | 0.85 | 0.98 | 1.10 | 1.22 | 1.34 | 1.46 |
| $\Delta T_a$ °C | 16.4 | 14.1 | 12.3 | 10.9 | 9.8 | 8.9 | 8.2 |

5. Experimental results
The converter is constructed according to the circuit shown in Fig.1 and the structure shown in Fig.2. The models of large fan and two small fans are BFB1224GH and BFB1024H respectively. When the output is 4kW and room temperature is 21°C, the main components temperature is shown as in Table 4. The baseplate temperature in Table 1 is the baseplate temperature of the primary full-bridge region. Temperature data is obtained by Fluck Ti30 thermal imager.

Table 4 Main components temperature in room temperature

| Points          | $T$ °C | Points          | $T$ °C |
|-----------------|--------|-----------------|--------|
| T’s core        | 81     | T’s windings    | 72     |
| $L_1$’s core    | 57     | $L_1$’s windings| 58     |
| $L_1$’s core    | 57     | $L_1$’s windings| 73     |
| baseplate       | 46     |                 |        |

Experiments at different ambient temperatures are carried out in the temperature test chamber. The baseplate temperature of primary full-bridge is shown in Table 5. Where, the temperature is measured by the LM35 temperature sensor.

The Experimental results in Table 4 and Table 5 show that the baseplate temperature rise $\Delta T_s$ of the heat sink is less than 35°C. The temperature rise of magnetic components is less than 70°C. The converter can work reliably at 70°C ambient high temperature.

Table 5 Baseplate temperature in different ambient temperature

| Ambient temperature °C | $T_s$ °C | $\Delta T_s$ °C |
|------------------------|---------|-----------------|
| 14                     | 39      | 25              |
| 55                     | 82      | 27              |
| 65                     | 94      | 29              |
| 73                     | 104     | 31              |

6. Summary
(1) According to the circuit structure of converter, the loss of main components was given, and an air-cooled heat dissipation structure was proposed. The centrifugal fan was embedded into the heat sink, and the fins of heat sink with stripes were adopted to expand the surface area of air-cooled heat dissipation.

(2) The primary full-bridge, the worst heat dissipation region, was selected as an example, the heat resistance model of air-cooled heat dissipation was constructed, the design process of air-cooled heat sink was illustrated, and then the pressure and volume of the fan were determined.
(3) The experimental results verified that the baseplate temperature rise of the heat sink was less than 35°C. The temperature rise of magnetic components was less than 70°C. The converter can work reliably at 70°C ambient high temperature. The power semiconductor devices and magnetic components have favorable thermal reliability.

Acknowledgments
This work was financially supported by Pre-research Project of Military Equipment for the 13th Five-year Plan, China (No.31512040130); Pre-research Project of Air Force Equipment for the 13th Five-year Plan, China (No.303040304).

References
[1] Yan Yangguang, Qin Haihong, Gong Chunying, et al. More Electric Aircraft and Power Electronic [J]. Journal of Nanjing University of Aeronautics & Astronautics, 2014, 46(1): 11-18.
[2] Z. P. Duan, Y. S. Muzychka. Experimental investigation of heat transfer in impingement air cooled plate fin heat sinks [J]. Journal of Electronic Packaging, 2006, 128(4): 412-418.
[3] Xue Kaichang. Research on Reliability Key Technologies of Geoelectric Field Grounded Source Transmitter [D]. Changchun: Jilin University, 2015.
[4] K. C. Xue, S. Wang, J. Lin, et al. Loss analysis and air-cooled design for a cascaded electrical source transmitter [J]. Journal of Power Electronics, 2015, 15(2): 530-543.
[5] Dai Guosheng. Heat transfer [M]. 2nd ed., Beijing: High Education Press, 2011.
[6] S. Y. Kim, R. L. Webb. Analysis of convective thermal resistance in ducted fan-heat sinks [J]. IEEE Transactions on Components and Packing Technologies, 2006, 29(3): 439-448.
[7] S. W. Karng, J. H. Shin, H. S. Han, et al. Thermal performance of a thermoelectric air-cooling system with heat sinks [C]. 12th IEEE Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems. Las Vegas: IEEE, 2010: 1-7.