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Research on the Pin Fin Efficiency and Structure

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Abstract

The performance of pin fin heat sink can be to measure through the temperature field. The temperature field and efficiency of the Pin Fin were analyzed, Pin fin efficiency curve was drowned also the distribution of the temperature field along the length of the pin fin curve was drawn. Thermal resistance was composed by thermal resistance of Aluminum substrate, thermal resistance of convective heat transfer and the thermal resistance of the cooling liquid. The change rule was studied through the calculation on Aluminum plate thermal resistance, thermal resistance of convective heat transfer and the thermal resistance of the cooling liquid. Its change regularity was simulated by toolbox In the MATLAB, and it was found that thermal resistance of convective heat transfer effect on the efficiency was most obvious in a certain amount of the heat and flow for thermal resistance of the Pin-fin radiator under the premise. The structural parameters of radiator were related to the size of thermal resistance.

Keywords: *radiator; convective heat transfer, thermal resistance; optimum design；efficiency*

1. Introduction

Research of electric vehicles was the inevitable trend of development in the world oil energy shortage environment. IGBT was a high power device in power electronic device installed in electric vehicles, it was requationuired that there were the advantages of high reliability, high power density, high efficiency, etc for the power electronic device.

When IGBT worked normally and it emitted enormous heat, a large number of electronic devices in controller were particularly affected by temperature. High temperature would seriously affect the reliability of electronic devices, therefore, how to effectively take the heat generated by the IGBT away was a very crucial problem [1],[2].

The problem of engineering design was changed into a mathematical model, then optimization method and its calculation program were selected according to the features of mathematical model. The necessary simplification was made and the optimal solution was obtained by using computer. So it was very important to improve the efficiency of the radiator by the research on the optimization of the radiator structural parameters [3],[4].

Due to the rapid development of computer technology, optimization designing in engineering could be solved. A solid platform was build for the optimization engineering problem by MATLAB [5],[6].

2. The Temperature and The Efficiency

According to the Factors of the environmental conditions, radiator structure was studied.

2.1. Figures and Tables

Radiator was simplified model as shown in Figure 1. As shown in Figure 2, pin fin radiator for a channel size structure, w as channel width, L as the channel length,  as needle rib spacing, d as pin-fin diameter.

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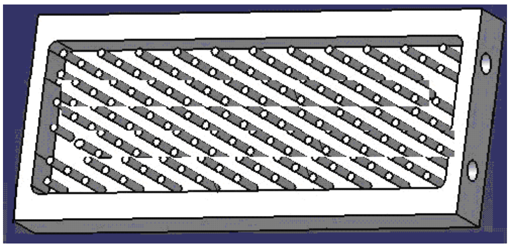


Figure 1. Radiator Rodel

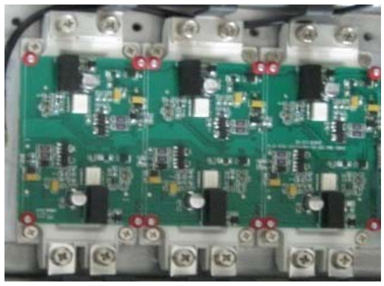


Figure 2. IGBT and Radiator Assembly

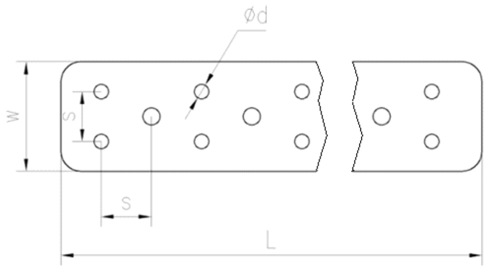


Figure 3. Pin Fin Radiator Channel Size

2.2 Heat Transfer Process of Pin Fin .

High power device IGBT generated heat conduction out through heat radiator aluminum substrate, coolant and pin fin surface convective heat transfer and cooling fluid convection heat [5],[7].

The process of the heat of conduction included the heat dissipating capacity of aluminum substrates ϕ_{cond}, convective heat transfer ϕ_{conv}, convective heat transfer of cooling liquid ϕ_{flud}

Equation1 was the heat conduction equation of Aluminum plate

$$\phi_{cond} = \frac{\lambda}{\delta} A(t_1 - t_2) \tag{1}$$

where, λ was thermal conductivity for aluminum plate，W/m·℃; δ was thickness of an aluminum substrate, mm. A was effective heat transfer area for aluminum substrate, m^2; t_1 was upper surface of aluminum substrate mean temperature, t_2 was mean temperature of aluminum substrate lower surface.

Convective heat transfer was expressed as

$$\phi_{conv} = t_2 - t_f \big/ (1/h_{av}\,(\eta_{fin} A_{fin} + A_{wall})) \tag{2}$$

where, t_f was coolant average temperature, ℃; h_{av} was the convective heat transfer coefficient, w/（m k）; η_{fin} was efficiency for the pin fin; A_{fin} was the area of side for the Pin-fin, m^2; A_{wall} was not occupied the wall area of the Pin-fin , m^2.

Convective heat transfer of cooling liquid for Equation 3

$$\phi_{flud} = C_P Q_m (t_{out} - t_{in}) \tag{3}$$

where, c_p was constant pressure ratio heat capacity , j·kg-1·k-1; Q_m was the mass flow rate,kg·s-1, t_{out} was outlet temperature for the waterway, ℃. t_{in} was inlet temperature for the waterway, □.

By the law of conservation of energy to get:

$$\phi = \frac{t_1 - t_{in}}{\frac{\delta}{\lambda A} + \frac{1}{h_{\partial V}(\eta_{fin} A_{fin} + A_{wall})} + 2Q_m C_p} \tag{4}$$

Where, $R_{cond} = \delta / \lambda A$, R_{cond} was thermal resistance for aluminum substrate, $R_{conv} = 1 / (h_{av}(\eta_{fin} A_{fin} + A_{wall}))$, R_{conv} was convective heat transfer resistance, $R_{flud} = 2C_P Q_m$, R_{flud}, as thermal resistance generated by the coolant.

2.3. Radiator Efficiency.

According to the water cooling radiator efficiency formula [8]:

$$\eta = \frac{\triangle T_m}{\triangle T_s} = \frac{\triangle T_m}{\triangle T_m + \phi(R_{cond} + R_{conv})} \tag{5}$$

where, ΔTm was the average coolant temperature rise , ΔTs was average temperature elevated for radiator.

The heat and flow of the IGBT was under certain preconditions, ΔTm was determined. When the structure of aluminum plate was determined, the thermal resistance of aluminum plates also would be determined, the efficiency of heat sink depended on convection thermal resistance R_{conv}.As thermal resistance R_{conv} of the convective heat transfer decreased, coolant temperature rise increased in proportion to the share of temperature, the heat brought by coolant became bigger and so the higher the efficiency.

2.4. The Pin Fin Temperature Field

Heat generated by power loss in high power devices first was conducted to the secondary heat conduct surface consisted by the pin fin and aluminum lower surface by means of aluminum plate heat conduction. And then heat was carried out in this way of the coolant and the secondary heat exchange surface transfer convection heat. As a result, the aim of heat transferring and cooling was realized [6],[8].

The temperature field distribution in the pin fin was relevant to the length, diameter and space, etc. There ware temperature gradient in axial direction. The radial temperature gradient was ignored. According to Fourier's Law, the heat transfer rate in the section was:

$$Q_x = -\lambda A \frac{dT}{dx} \tag{6}$$

Where, λ was material coefficient of thermal conductivity, $\mathrm{w/m^2 \cdot ℃}$; A was pin fin sectional area, m^2;

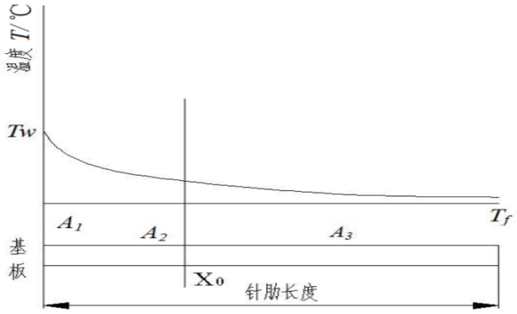
According to the Law of conservation of energy, the temperature distribution functions as follows:

$$q(x) = q_w \frac{\cosh(m(l-x))}{\cosh ml} \tag{7}$$

Where, l was pin fin height, m; m was pin fin parameter, function of material property and physical property of coolant.

According to the whole secondary heat exchange surface of the heat sink, it was divided as follows: aluminum plate area free from pin fin A_1, pin fin lower part area taking x_0

which was the turning point in pin fin temperature distribution as boundary A_2, pin fin upper area A_3. The whole heat conduction of the secondary heat exchange surface was the addition of the three points. The distribution of pin fin temperature was depicted in Figure 4



Tw——aluminum plate temperature, 0C;
Tf ——average fluid temperature, 0C

Figure 4. Temperature field the distribution along the pin fin length

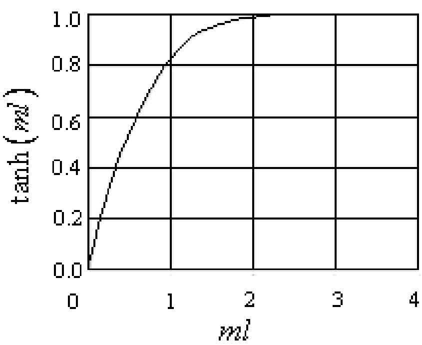


Figure 5. The pin fin efficiency curve

2.5. The Pin Fin the efficiency

As shown in figure 5, the root temperature of pin fin was the same as the aluminum plate temperature. In the interval from root to $x_{0,}$ the temperature change amplitude was big. In the interval from x_0 to the end temperature, the tendency was nearly flat. The end temperature was nearly equationual to the average fluid temperature. From the consideration on the heat dissipation, the pin fin was not the longer, the better. Thus, the average temperature on the pin fin surface was lower than the one without temperature setting, and the temperature difference between aluminum lower surface and the fluid was lower than the one without pin fin. As a result, it could reduce fouling.

According to the relationship between heat conduction equationuation and hyperbolic function, the pin fin efficiency was expressed as: $E = \tanh(ml)/ml$, it's main influence factor was ml. While $ml = \sqrt{(2a/\lambda R)}l$, α was the convection heat transfer coefficient, λ was the pin fin material coefficient of thermal conductivity, d was the pin fin diameter, and l was the pin fin length.

The pin fin efficiency E varied with ml. From Figure 5, it can be seen that $\tanh(ml)$ tended to be a constant with increase of ml. When $ml \geq 2$, E was remained unchanged as ml increased in general.

In the premise that the material coefficient of thermal conductivity λ was fixed, the smaller the diameter d of pin fin, the greater the length l of pin fin and the larger convection heat transfer coefficient α, but the efficiency E was higher. When $ml \approx 1.2$, the efficiency E reached the peak. So to ensure higher efficiency E, we can choose fine and high pin fin when the convection heat transfer coefficient α is small, and we can choose thick and short one in the opposite case.

In order to ensure a high pin fin efficiency of E, when the convective heat transfer coefficient α was relatively small fine and high pin fin was selected, when the convective heat transfer coefficient α was larger the coarse and short pin fin was selected.

3. Analysis of Pin fin Structure Parameter

As the main factors affecting the efficiency of heat transfer of radiator was convective heat transfer and the flow of fluid through the needle rib had a complex fluid mechanics characteristics. So the complexity of the process was mainly manifested in the local heat transfer coefficient distribution of being the spoiler needle ribbed surface. When the coolant flows through the pin fin surface, due to the complexity of structure, the size of average heat transfer coefficient was affected by spacing, diameter and length of the pin fin [9] .Therefore, effective parameters identified of radiator pin fin had the important meaning for increasing the convective heat transfer coefficient; reducing convective heat transfer resistance and improving heat transfer efficiency of radiator [10].

In the premise of meet the system pressure loss and flow certain, to ensure the highest efficiency had been become the key of radiator designed through the optimization of diameter d , height l and spacing s of pin-fin. Therefore, the convection heat transfer resistance became minimum through diameter, length and spacing of pin-fin was optimized, thus, the optimization design of radiator was achieved [6],[11].

Definition of dimension heat resistance R_{flud} ,then :

$$R_{flud} = R_{conv}\eta_{fin} = \frac{1}{\eta_{fin}A_{fin} + A_{wall}} = \frac{1}{\eta_{fin} \times 3\pi dl + 44s - 0.75\pi d^2} \tag{8}$$

Among them, $\eta_{fin} = \tanh ml/ml$, $m = \sqrt{h_{av}}/\sqrt{\lambda d}$. $h_{av}/\lambda d \ge 1$, so $e^{-ml} \to 0$, then $\tanh ml \approx 1$.

If the efficiency η of radiator was higher, the convective heat transfer resistance R_{conv} was requationuired smaller, thus, R_{conv} and R_{flud} in the optimization goal was consistent.

4. Optimum Design

Access function:

$$f(d, l, s) = 3\pi d \cdot \frac{\sqrt{\lambda d}}{\sqrt{h_{av}}} - 0.75\pi d^2 + 44s \tag{9}$$

For the minimum value of the thermal resistance R_{flud}, namely maximum value of formula (9). In selection of the optimized parameter [12][13]. which could be fixed to any two parameters, it was only with a parameter $f(d, l, s)$ relevant. on the $f(d, l, s)$ derivation, research on derived function in the variable region of the polarity. It derives the maximum of a function.

4.1. Optimum Design d .

When l 、s were certain in the interval [2.5, 4.5] , For function f derivation，namely:

$$\frac{\partial f}{\partial d} = 3\pi \times \frac{3}{2} \times d^{\frac{1}{2}} \times \left(\frac{\lambda}{h_{av}}\right)^{\frac{1}{2}} - \frac{3}{2}\pi d \tag{10}$$

Let $3\sqrt{\lambda}/\sqrt{h_{av}} = k$, then: Equation.10 equationual to $\frac{\partial f}{\partial d} = \pi \times \frac{3}{2} \times d^{\frac{1}{2}} \times k - \frac{3}{2}\pi d$.

If $\frac{\partial f}{\partial d} < 0$, it was requationuired $d > k^2 = 9\lambda/h_{av}$, and $0 < 9\lambda/h_{av} < 1$ then $d \ge 2.5$, so hypothesis was set up. $f(d, l, s)$ Monotone decreased in the $4.5 \ge d \ge 2.5$. When d decreased, $f(d, l, s)$ increased, R_{flud} decreased.

4.2. Optimum Designing l .

When d , s were certain, in the interval [15,19], through the function $f(d, l, s)$ on l derivation, $\frac{\partial f}{\partial l} = 0$, so l did not affect the $f(d, l, s)$ monotonicity , l had little influence on the thermal resistance, effect of $f(d, l, s)$ on the thermal resistance could be ignored.

4.3. Optimum Design S

When d , l were certain, in the interval [9, 12], through the function $f(d, l, s)$ on S derivation, $\frac{\partial f}{\partial s} = 44$, because of $\frac{\partial f}{\partial s} > 0$ so $f(d, l, s)$ monotone decreasing in the $12 \ge s \ge 9$,when S increased, the thermal resistance R_{flud} decreased.

By calculation, it could effectively reduce the thermal resistance of convective heat transfer to reduce needle rib needle diameter and increase the spacing between the ribs, so as to further improve the efficiency of the radiator.

5. Optimization Simulation

5.1. Establishment of the Objective Function

For a maximum of the objective function $f(d, l, s)$, and the optimization function could only solve the objective function minimization. If the requirements were the goal to maximize for optimization objective function, it could be realized by the negative value of the objective function, namely, $-f(d, l, s)$, so the objective function was expressed as $g(d, l, s) = -f(d,l,s)$ [14].

The coefficient range of water forced convective heat transfer was 1000 - 15000 W / m K, Taking the average coefficient of convection heat transfer $h_{\partial v} = 1200$ w / MK, thermal conductivity coefficient of aluminum alloy materials 162 w /mk,

The objective function was expressed as $g(x_1, x_2) = x_1^{3/2} - 2.4x_1^2 + 44x_2$

Constraint function：

$2x_1 - x_2 \le 0$, $x_1 + x_2 \le 22$, $2.5 \le x_1 \le 6$, $9 \le x_2 \le 12$

5.2. The MATLAB Optimization Simulation Result .

By editing the M file[6],[15]:

functionf=objfun2(x)， f=2.4*x(1)^2-x(1)*sqrt(x(1))-44*x(2);

In the command window, the preparation of the main program, the output results:

```
X = 2.5000   11.0000
FVAL = -472.9528
EXITFLAG = 1
OUTPUT = iterations: 2
funcCount: 6
lssteplength: 1
stepsize: 0
algorithm: 'medium-scale: SQP, Quasi-Newton, line-search'
   firstorderopt: 0
  constrviolation: 0
      message: [1x834 char]
```

5.3. Optimal Solution

Through MATLAB simulation show that convergence of objective function was achieve after 2 iterations, the optimal solution was that $d = 2.5$ mm, $s = 11$ mm.

6. Conclusion

1) When ml≈1.2, the pin fin efficiency E reached the peak, so fine and high pin fin was chosen to ensure higher efficiency E when the convection heat transfer coefficient α was small, and thick and short one was chosen in the opposite case.
2) The distribution of temperature field in the pin fin was relevant to the length, diameter and spacing, etc.
3) The radiator efficiency depended mainly on the convective heat transfer resistance, optimization of radiator structure could achieve the purpose of reducing thermal resistance.

4) By theoretical calculation and verification of simulation results, it could be achieved to improve the efficiency of the radiator through pip fin s was increased and pin-fin diameter d was reduced, thus this conclusion played a guiding role for actual design.
5) By the establishment of objective function and constraint function, there was a broad application prospects for MATLAB in engineering optimization design.

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