DESIGN HEAT DISSIPATION FOR MOSFET

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ABSTRACT

Currently, high power density and compact size converters are widely used and being extensively developed. Heatsinks also occupy a large volume affecting the power density, size of the converters and ensuring stable operation. This paper presents a model for estimating the losses of MOSFETs, thermal resistance of heat sink when incorporating the impact of cooling fans. Following this, a proposition is presented for the selection of appropriate heatsink and fan parameters. The validity of the proposed model and the effectiveness of these techniques are verified through simulations conducted using Ansys Icepak.

Keywords: *Thermal management, heatsink modeling, forced convection, MOSFET power loss, cooling fan.*

1. INTRODUCTION

The advancement of high-power-density and compact converters has accentuated the significance of addressing losses, particularly in components known to generate substantial power losses, such as MOSFETs, IGBTs, and diodes. Excessive losses can lead to semiconductors overheating, resulting in reduced reliability and premature failure. To mitigate this issue heatsinks are used to increase the heat flow away from semiconductors devices.

This paper presents an thermal model for MOSFET and a heat dissipation system. The schematic representation of the heat dissipation system, as illustrated in Fig. 1, comprises a heatsink and a fan. The paper outlines a systematic approach for selecting an appropriate heatsink, supported by detailed procedures. The calculated results are subsequently validated through both simulation and experimental data.

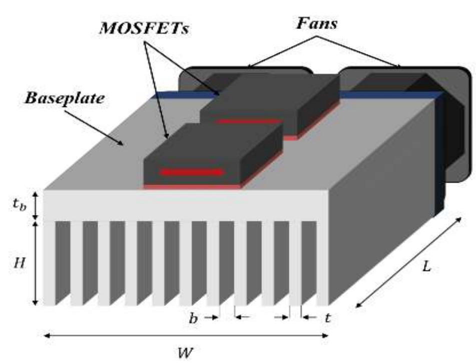

Fig. 1. *Structure of heat dissipation system*

2. THERMAL MODEL

Power dissipation results in the generation of thermal energy at the junction of the MOSFET. Heat is conducted from the junction to the case, thermal interface material (TIM), and heatsink through conduction. Then heat is transferred to external environment through convection. The thermal resistance from the junction to ambient illustrated in Fig. 2. Here, R_{thJC} represents the thermal resistance from the junction to the case of the MOSFET. R_{thCH} signifies the thermal resistance from the case to the heatsink. R_{thHA} is a composite term encompassing both the convection-based thermal resistance from the heatsink to the ambient environment and the thermal resistance due to conduction within the heatsink.

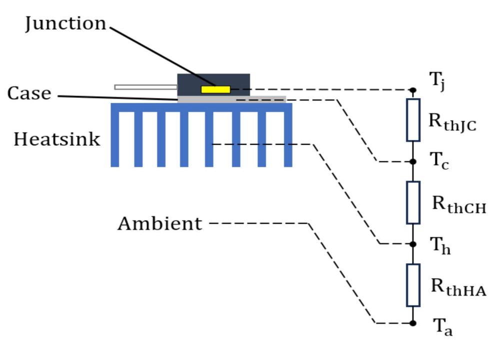

Fig. 2. *Thermal Network*

2.1. Mosfet Thermal Model

The total losses in MOSFETs manifest as thermal energy at the MOSFET junction, encompassing both conduction and switching losses. The primary types of losses in MOSFETs are conduction and switching losses.

$$P_l = P_c + P_{sw} \quad (1)$$

where, P_l is total power loss, P_c is conduction loss, P_{sw} is switching loss and they are calculated according to formulas (2) and (3) below.

$$P_c = R_{DS,on}.I_{D,rms}^2 \quad (2)$$

where, $R_{DS,on}$ is the drain to source on-state resistance. $I_{D,rms}$ is RMS value of current passing through MOSFET.

MOSFETs manifest two distinct switching modes, which are hard switching and soft switching. Switching loss is almost negligible for MOSFET with soft switching. For MOSFET with hard switching, switching loss is calculated according to formula below:

$$P_{sw} = P_{sw,on} + P_{sw,off} \quad (3)$$

with,

$$P_{sw,on} = U_{DD}.I_{D,on}.\frac{t_{ir}+t_{vf}}{2}.f_s \quad (4)$$

$$P_{sw,off} = U_{DD}.I_{D,off}.\frac{t_{vr}+t_{if}}{2}.f_s \quad (5)$$

where, $P_{sw,on}$ and $P_{sw,off}$ are the losses caused during turn-on and turn-off transient of MOSFET.

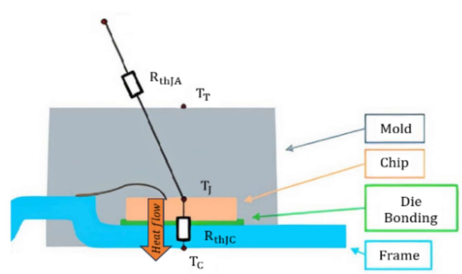

Fig. 3. *MOSFET thermal model*

According to [6], the basic structure of MOSFET package able to dissipate heat from the back surface consists of a lead frame ("Frame" in Fig. 3), die bonding between the chip and the lead frame, the MOSFET chip ("Chip"), and the resin package ("Mold"). The "junction" in the explanation of symbols refer to the PN junction, or more simply, the chip. The chip is the primary source of heat for the MOSFET. Because the 'Mold' has low thermal conductivity, the chip primarily dissipates heat through the back side where the 'Frame' offers higher thermal conductivity.

The parameter denoted as R_{thJA} represents the thermal resistance between the MOSFET junction and the surrounding ambient environment, playing a fundamental role in thermal analysis. R_{thJC} is the thermal resistance between junction and case, essential for thermal calculations when back surface of MOSFET is mounted on the board or when a heatsink is mounted in close contact. R_{thJA} and R_{thJC} can be used to calculate the temperature rise of MOSFET under various operating conditions. This information helps in determining whether additional cooling methods, like heatsinks or thermal management strategies, to ensure the MOSFET operates reliably and efficiently. T_J signifies the junction temperature, a critical parameter that should not surpass the specified absolute maximum rating, denoted as T_{Jmax}. The values for thermal resistance and temperature above can be found in the datasheet.

2.2. Heat Dissipation System Thermal Model

2.2.1. Heatsink thermal model

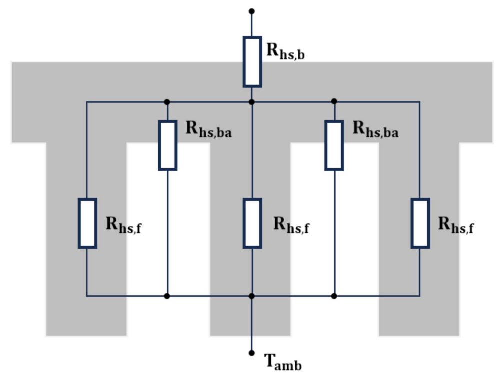

Fig. 4. *Heatsink thermal model*

The thermal resistance of a heatsink, R_{hs}, is contingent upon several factors, including surface area, convection flow rate, cooling method, and more. R_{hs} can be estimated base on analytical and empirical equation in [2]-[5]. Here cooling method is forced convection using airflow generated by a fan. The heatsink plays a role as an obstruction a pressure drop between the inlet and outlet of the heatsink. This reduces the airflow passing through the heatsink. The method for calculating the thermal resistance of the heatsink and characteristics of a pressure drop of the heatsink is presented below.

2.2.1.1 Heatsink thermal resistance

As depicted in Fig. 4, the thermal resistance of the heatsink include $R_{hs,b}$ – the conduction thermal resistance of the heatsink baseplate, $R_{hs,ba}$ – the convection thermal resistance of the heatsink baseplate to ambient and $R_{hs,f}$ – the thermal resistance of heatsink fin. The overall heatsink thermal resistance is given by:

$$R_{hs} = \frac{1}{\frac{N}{R_{hs,f}} + \frac{N-1}{R_{hs,ba}}} + R_{hs,b} \quad (6)$$

where, N is the number of fins.

The thermal resistance $R_{hs,b}$ is calculated by:

$$R_{hs,b} = \frac{t_b}{k_{hs} L W} \quad (7)$$

where, k_{hs} is the thermal conductivity of the heatsink, t_b is the baseplate thickness, L is the heatsink length, W is the heatsink width.

To calculate the value of convection thermal resistance, it is necessary to calculate the value of convection heat transfer coefficient – *h*. *h* can be determined through dimensionless convection heat transfer coefficient – Nusselt number:

$$h = \frac{Nu_b . k_{air}}{b} \quad (8)$$

where, k_{air} is the conductivity of air, b is heatsink fin spacing.

The Nusselt number is strongly linked to Reynolds number of the fluid and it can be expressed using the following formula:

$$Nu_b = \left[\left(\frac{Re_b^* Pr}{2} \right)^{-3} + \left(0.664 \sqrt{Re_b^*} Pr^{\frac{1}{3}} . \sqrt{1 + \frac{3.65}{\sqrt{Re_b^*}}} \right)^{-3} \right]^{-\frac{1}{3}} \quad (9)$$

where Re_b^* is the channel Reynolds number which is determined through the Reynolds number R_b.

$$Re_b^* = Re_b . \frac{b}{L} \quad (10)$$

$$Re_b = V . \frac{b}{\nu} \quad (11)$$

and Pr is the Prandtl number.

$$Pr = \frac{\nu}{\alpha} \quad (12)$$

where, V is the average flow velocity in the heatsink channel, ν is the kinematic viscosity of air, α is the thermal diffusivity of air and under the ambient temperature condition of 25 ℃, $\nu = 1.56 \cdot 10^{-5}\ m^2/s, \alpha = 22.39 \cdot 10^{-6}\ m^2/s$.

So, from the calculated value of h above, $R_{hs,ba}$ is given by:

$$R_{hs,ba} = \frac{1}{h.b.L} \quad (13)$$

The thermal resistance $R_{hs,f}$ represents the combined conduction and convection thermal resistance of an individual heatsink fin and is determined by:

$$R_{hs,f} = \frac{1}{\sqrt{hPk_{hs}A_c}\tanh(mH)} \quad (14)$$

with,

$$m = \sqrt{\frac{hP}{k_{hs} Ac}} \quad (15)$$

where, P is the circumference of the fin and A_c is the cross-sectional area of the fin.

$$P = 2.(t + L), A_c = t.L \quad (16)$$

Through the calculated equations, the velocity of the convective flow is directly proportional to h and h is inversely proportional to the convection thermal resistance. This implies that as the convective flow velocity increases, the convection thermal resistance decreases.

2.2.1.2. Pressure Drop

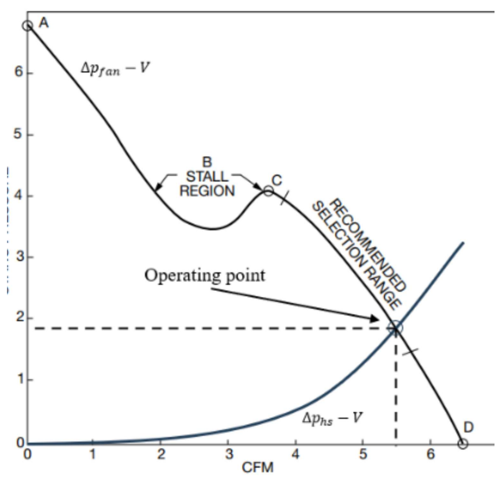

Fig. 5. *Fan curve $\Delta p_{fan} - V$ and the characteristic $\Delta p_{hs} - V$ of the heatsink*

Pressure drop in the heatsink refers to the decrease in pressure that occurs as air passes through the fins and channels of the heatsink. This pressure is typically measured in units of pressure, such as Pascals (Pa) or inches of water (inH2O). Pressure drop in a heatsink is an important consideration in thermal management and heat dissipation. It can affect the overall performance of cooling systems and impact the efficiency of heat transfer from components to the surrounding environment. The pressure drop of heatsink, denoted as Δp_{hs}, according to [4], is given by:

$$\Delta p_{hs} = \left(\frac{f_{app} N(2HL + bL)}{HW} + K_C + K_e \right)\left(\frac{1}{2}\rho V^2 \right) \quad (17)$$

where, ρ is the air density (at 25 °C, ρ = 1.184 kg/m^3) and f_{app} is the apparent friction factor f_{app} is

$$f_{app} = \frac{1}{\mathrm{Re}_{D_h}} \left[\left(\frac{3.44}{\sqrt{\frac{L}{D_h \mathrm{Re}_{D_h}}}} \right)^2 + \left(f.\mathrm{Re}_{D_h} \right)^2 \right]^{\frac{1}{2}} \quad (18)$$

where, D_h is hydraulic diameter of the channel and $f.\mathrm{Re}_{Dh}$ is the fully developed flow friction factor Reynolds number group given by:

$$f.Re_{D_h} = 24 - 32.527\left(\frac{b}{H}\right) + 46.721\left(\frac{b}{H}\right)^2 - 40.829\left(\frac{b}{H}\right)^3 + 22.954\left(\frac{b}{H}\right)^4 - 6.089\left(\frac{b}{H}\right)^5 \quad (19)$$

and the friction factor for sudden contraction K_c and sudden expansion K_e are

$$K_c = 0.42(1 - \sigma^2)$$
$$K_e = (1 - \sigma^2)^2 \quad (20)$$

with,

$$\sigma = 1 - \frac{N.t}{W} \quad (21)$$

2.2.2 Fan characteristic

As mentioned earlier, the airflow velocity influences the *h* coefficient. Therefore, fan is used to increase the airflow velocity to enhance the cooling efficiency.

The most commonly used fan characteristic is the relationship between static pressure and volume flowrate for a constant impeller speed (RPM). As shown in Fig. 5, this is the fan curve $\Delta p_{fan} - V$. Point A represents the point of zero air flow on the static pressure curve. Point B depicts the stall region of the static pressure curve. Operation in this area is discouraged because of erratic airflow that generate excessive noise and vibration. Point C depicts what is referred to as the peak of the static pressure curve and point D is the point of maximum airflow. Curve segment CD is the stable portion of the fan curve and is where the fan is selected to operate [7]. The operating point of the fan is established by identifying the point of intersection between the two characteristics curves $\Delta p_{fan} - V$ and $\Delta p_{hs} - V$. From there, it is possible to calculate the airflow velocity through the heatsink using operating point above.

3. HEATSINK SELECTION PROCEDURE

3.1. Heatsink selection procedure

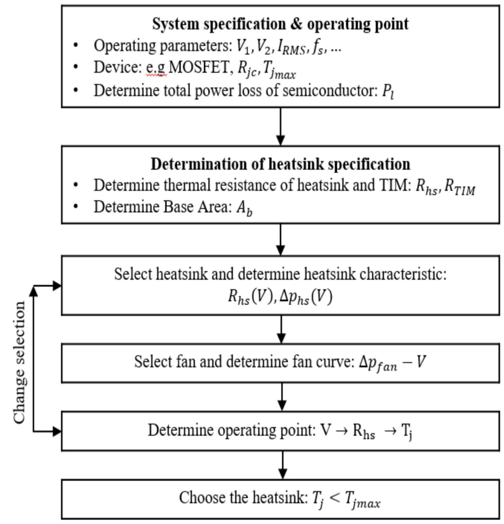

Fig. 6. *Heatsink selection procedure*

In the first step, determine the operating point and parameter of switch to calculate the losses. In second step, determine the maximum thermal resistance heatsink, thermal resistance of the TIM and the dimension of the heatsink baseplate. The maximum thermal resistance of the heatsink from [4] given as:

$$R_{hs,\max} = \frac{T_{j,\max} - P_l(R_{thJC} + R_{thCH}) - T_{amb}}{P_l} \quad (22)$$

Then, an internal iteration loop is used to find operating point of fan base on the selected fan and heatsink. From that, the junction temperature of the MOSFET can be determined. The optimal choice of the fan and heatsink is based on the criterion: $T_j < T_{jmax}$. Detail regarding the selection of the fan and heatsink are presented below. Fig. 6 illustrates the procedure for selecting suitable heatsink, fan and TIM for power electronic converter.

3.1.1 Selection heatsink

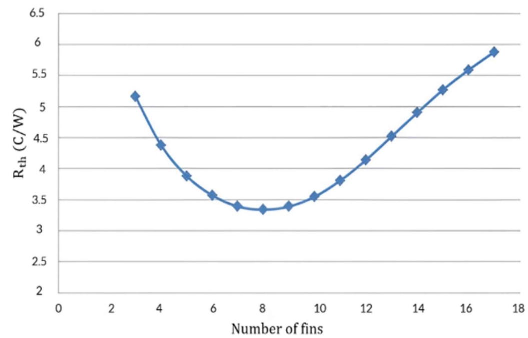

Fig. 7. *Thermal resistance of heatsink for various number of fins*

An important parameter to consider when choosing a heatsink using forced convection method is the number of fins. The larger number of fin results in a larger surface area of the heatsink but heatsink thermal resistance does not increase proportionally. Fig. 7 illustrates the thermal resistance of the heatsink for various number of fins. While increasing the number of fins does increase the surface area, it also leads to higher the pressure drop across the heatsink, reducing the convective airflow velocity. Consequently, the relationship between thermal resistance and the number of fins follow a concave curve. Therefore, the optimal point is the point in the middle of the curve.

An important step in the selection of a heatsink is determining of the appropriate length of the fin. This is crucial because the temperature decreases exponentially along the fin until it eventually equals the ambient temperature at a certain length. The portion of the fin beyond this length does not contribute to heat transfer because it has reached the ambient temperature, as shown in Fig. 8. Details about selecting the appropriate fin length are presented in [1].

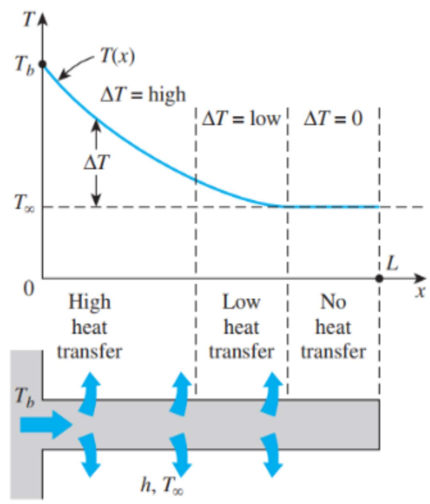

Fig. 8. *Region near the fin tip makes little or no contribution to heat transfer*

3.1.2. Selection cooling fan

Selecting a cooling fan such that the operating point falls within the stable operational range is crucial. Additionally, when connecting two fans with the same characteristic in parallel the expected result is a doubling of the air flow. However, in practice, the airflow from each fan often interferes with the other, so the actual flow rate may not be exactly double. The operating points for two fans in parallel are determined in a similar manner to a single fan.

3.2. Applied for MOSFET IPA60R120P7

The analysis and selection procedure in the previous sections is applied for MOSFET IPA60R120P7 which has a power loss of 2.56 W.

Table 1. *Thermal Parameters of MOSFET, TIM and required Heatsink specifications.*

MOSFET IPA60R120P7	R_{jc}	$4.49\ K/W$
	Dimensions	$15.7 \times 10 \times 4.5\ mm^3$
	$T_{j,max}$	$70\ °C$
TIM	k_{TIM}	$1.2\ Wm^{-1}K^{-1}$
	L_{TIM}	$0.5\ mm$
Heatsink specification	$R_{hs,max}$	$9.15\ K/W$
	Min. Baseplate	$65\ mm \times 43\ mm$

Table 2. *Geometrical and Thermal Parameters of the selected Heatsink.*

Heatsink width	W	43 mm
Heatsink length	L	65 mm
Baseplate thickness	t_b	2.5 mm
Fin height	H	13.5 mm
Fin spacing	b	4 mm
Fin width	t	1.5 mm
Thermal conductivity	k_{hs}	$236\ Wm^{-1}K^{-1}$

Table 3. *Calculation results for Force Convection Cooling*

Pressure Drop	Δp_{hs}	$0.42\ inchH_2O$
Flow Velocity	V	$4.99\ m/s$
Heat transfer coefficient	h	$40.57 Wm^{-2}K^{-}$
Thermal resistance	R_{hs}	$1.546\ K/W$

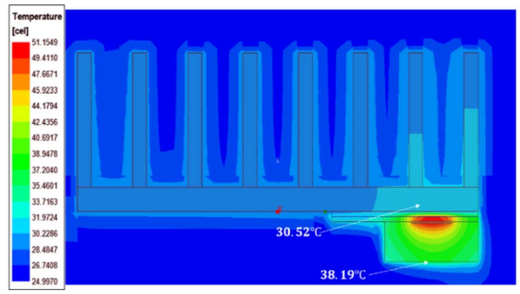

Fig. 9. *Simulation result*

The parameters of the MOSFET and TIM are given in Table 1 while the heatsink parameters and calculation results are given in Table 2 and Table 3. The maximum heatsink resistance is 9.15 K/W. To verify calculation result, the Icepak simulation is carried out by using software Ansys Electronic Desktop. Fig. 10 illustrates simulation result are the maximum junction temperature is 51.15°C , the maximum case temperature is 38.19°C.

The experimental investigation was performed based on MOSFET IPA60R120P7 and CFM-8025-13-20, as shown in Fig. 10. A constant current was supplied through the body diode of MOSFET, with the loss through the body diode is 2.56 W.

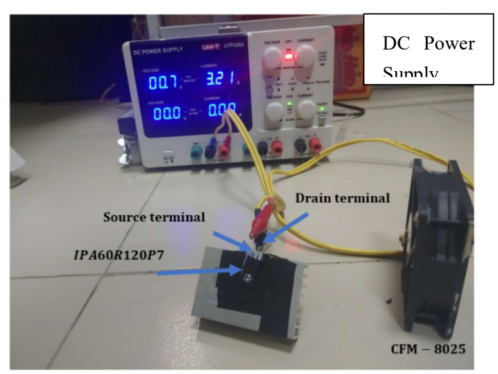

Fig. 10. *Experimental Setup*

TABLE 4. Calculation and simulation results of the junction and case temperature

	Calculation	Simulation
Junction	$51.29°C$	$51.15\ °C$
Case	$39.80\ °C$	$38.19°C$

TABLE 5. Simulation and experiment results of the heatsink base and MOSFET case temperature

	Experiment	Simulation
Heatsink Base	$29.8°C$	$30.52\ °C$
Case	$38.80\ °C$	$38.19°C$

From the results in Table 4 and Table 5, it can be observed that the thermal requirements have been addressed. With an error margin of approximately 10%, this outcome is considered acceptable.

4. CONCLUSION

This paper has provide an analysis of loss calculation in component, thermal modeling, calculation of heatsink's pressure drop, and method for determining the operating point on the fan curve. Subsequently, the calculation results were validated through experiment and simulation. The error between calculation, simulation and experiment is approximately 10%, which is considered acceptable selection.

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