– Chapter 3 –

Heat Dissipation Design Method

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This chapter describes heat dissipation design.

To operate the IGBT safely, it is necessary not to allow the junction temperature (Tj) to exceed Tjmax. Perform thermal design with sufficient allowance in order not for Tjmax. to be exceeded not only in the operation under the rated load but also in abnormal situations such as overload operation.

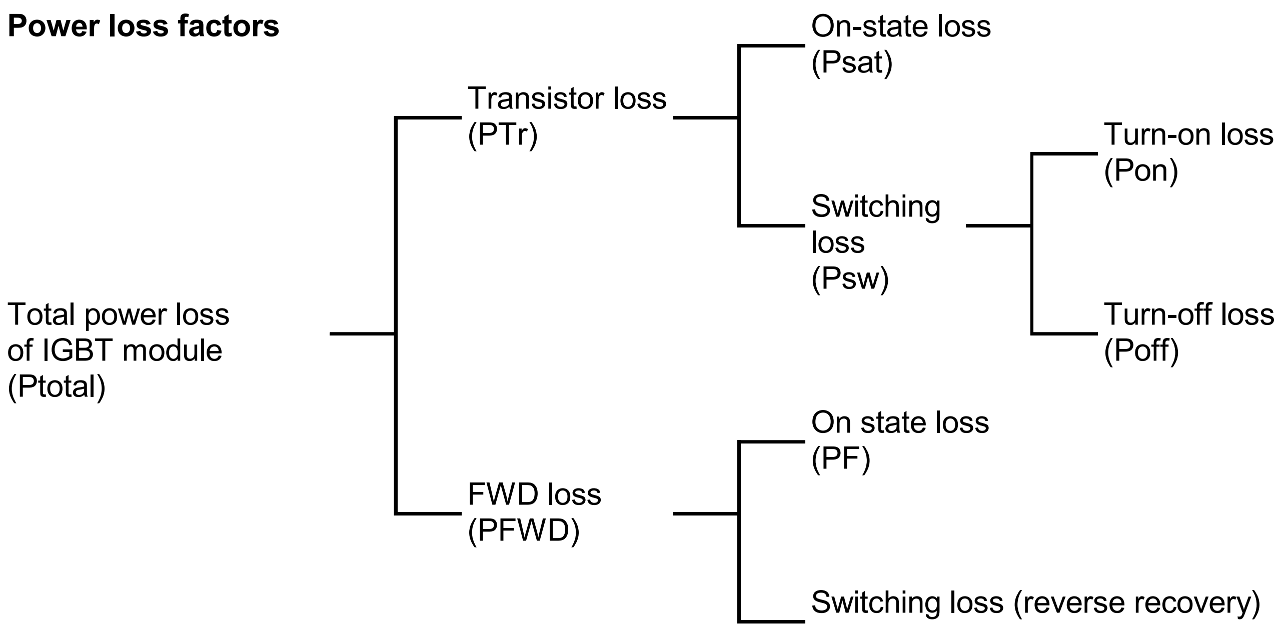
1. Power dissipation loss calculation

In this section, the simplified method of calculating power dissipation for IGBT modules is explained.

In addition, an IGBT loss simulator is available on the Fuji Electric WEB site (http://www.fujielectric.co.jp/xxxxx/). It helps to calculate the power dissipation and thermal design for various working condition with various Fuji IGBT modules.

1.1 Types of power loss

The IGBT module consists of several IGBT dies and FWD dies. The sum of the power losses from these dies equals the total power loss for the module. Power loss can be classified as either on-state loss or switching loss. A diagram of the power loss factors is shown as follows.



The on-state power loss from the IGBT and FWD elements can be calculated using the output characteristics, and the switching losses can be calculated from the switching loss vs. collector current characteristics on the datasheet. Use these power loss calculations in order to design a suitable cooling system to keep the junction temperature Tj below the maximum rated value.

The on-state voltage and switching loss values at standard junction temperature (Tj=150°C) is recommended for the calculation.

Please refer to the module specification sheet for these characteristics data.

1.2 Power dissipation loss calculation for sinusoidal VVVF inverter application

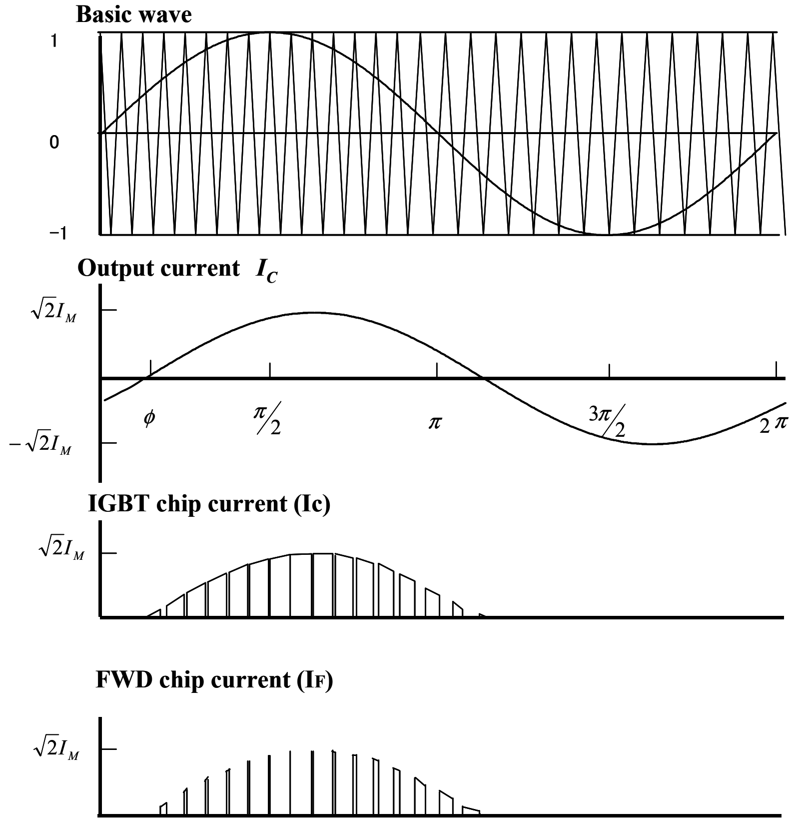


Fig.3-1 PWM inverter output current

In case of a VVVF inverter with PWM control, the output current and the operation pattern are kept changing as shown in Fig.3-1. Therefore, it is helpful to use a computer calculation for detailed power loss calculation. However, since a computer simulation is very complicated, a simplified loss calculation method using approximate equations is explained in this section.

Prerequisites

For approximate power loss calculations, the following prerequisites are necessary:

・ Three-phase PWM-control VVVF inverter for with ideal sinusoidal current output

・ PWM control based on the comparison of sinusoidal wave and saw tooth waves

On-state power loss calculation (Psat, PF)

As displayed in Fig.3-2, the output characteristics of the IGBT and FWD have been approximated based on the data contained in the module specification sheets.

On-state power loss in IGBT chip (P_{sat}) and FWD chip (P_F) can be calculated by following equations:

$$(P_{sat}) = DT\int_0^x I_C V_{CE(sat)} d\theta$$
$$= \frac{1}{2} DT\left[\frac{2\sqrt{2}}{\pi} I_M V_O + I_{M^2} R\right]$$

$$(P_F) = \frac{1}{2} DF\left[\frac{2\sqrt{2}}{\pi} I_M V_O + I_{M^2} R\right]$$

DT, DF: Average on-state ratio of the IGBT and FWD at a half-cycle of the output current. (Refer to Fig.3-3)

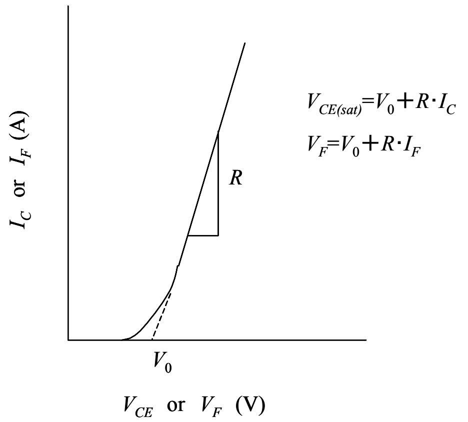


Fig. 2-2 Approximate output characteristics

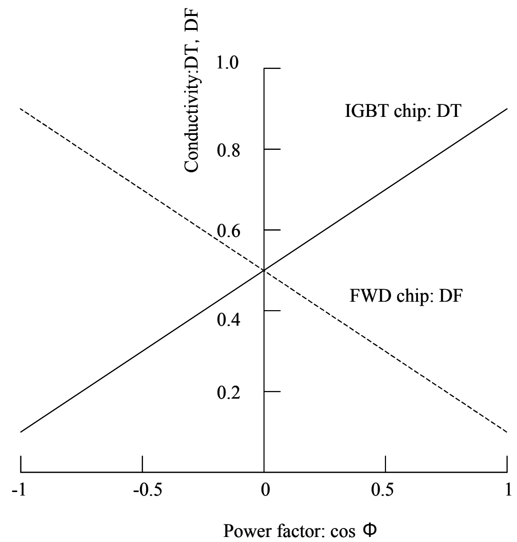


Fig.3-3 Relationship between power factor sine-wave PWM inverter and conductivity

Switching loss calculation

The characteristics of switching loss vs. I_C as shown in Fig.3-4 are generally approximated by using following equations.

$$E_{on} = E_{on'}(I_C / ratedI_C)^a$$

$$E_{off} = E_{off'}(I_C / ratedI_C)^b$$

$$E_{rr} = E_{rr'}(I_C / ratedI_C)^c$$

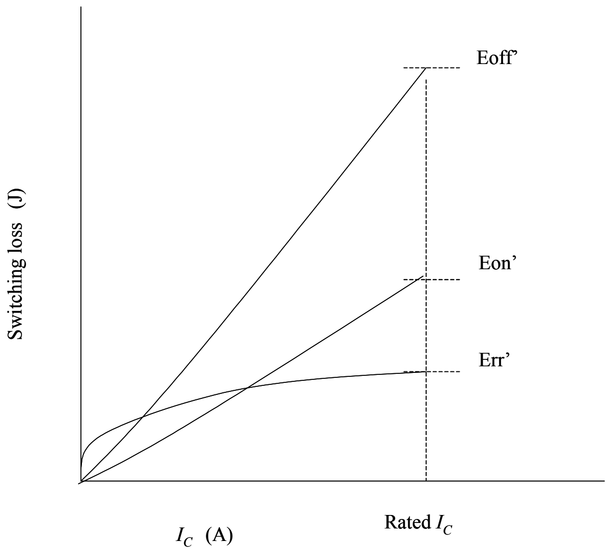


Fig.3-4 Approximate switching losses

a, b, c: Multiplier

E_{on}', E_{off}', E_{rr}': E_{on}, E_{off} and E_{rr} at rated IC

The switching losses can be represented as follows:

· **Turn-on loss (Pon)**

$$P_{on} = fo\sum_{K=1}^{n}(E_{on})k \qquad \left(n: Half-cycle\ switching\ count = \frac{fc}{2fo}\right)$$

$$= foE_{on}'\frac{1}{rated\ I_{C^a}}\sum_{k=1}^{n}(I_{C^a})k$$

$$= foE_{on}'\frac{n}{rated\ I_{C^a}\times\pi}\int_0^{\pi}\sqrt{2}I_{M^a}\sin\theta d\theta$$

$$= foE_{on}'\frac{1}{rated\ I_{C^a}}nI_{M^a}$$

$$= \frac{1}{2}fcE_{on}'\left[\frac{I_M}{rated\ I_C}\right]^a$$

$$= \frac{1}{2}fcE_{on}(I_M)$$

Eon(IM):Ic= Eon at IM

· **Turn-off loss (Poff)**

$$P_{off} = \frac{1}{2}fcE_{off}(I_M)$$

Eoff(IM):Ic= Eoff at IM

· **FWD reverse recovery loss (Prr)**

$$P_{off} \approx \frac{1}{2} fcE_{rr}\left(I_M\right)$$

E_{rr} when $E_{rr}(I_M)$:$I_C = I_M$

Total power loss

Using the results obtained in section 1.2.

IGBT chip power loss: $P_{Tr} = P_{sat} + P_{on} + P_{off}$

FWD chip power loss: $P_{FWD} = P_F + P_{rr}$

The DC supply voltage, gate resistance, and other circuit parameters will differ from the standard values listed in the module specification sheets.

Nevertheless, by applying the instructions of this section, the actual values can easily be calculated.

2. Method of selecting a liquid cooling jacket

The electrode terminals and the mounting base of the automotive IGBT power modules (6MBI400VW-065V/6MBI600VW-065V) are insulated, it is easy for mounting and compact wiring. It is important to select an appropriate liquid-cooling jacket because it is necessary to dissipate the heat generated at each device during operation for safety operation of the module. The basic concept in selecting a liquid cooling jacket is described in this section.

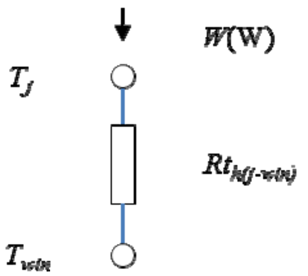
2.1 Thermal equation in steady state

Thermal conduction of IGBT module can be represented by an electrical circuit. In this section, in the case only one IGBT module mounted to a heat sink is considered. This case can be represented by an equivalent circuit as shown in Fig. 3-5 thermally.

From the equivalent circuit shown in Fig. 3-5, the junction temperature (Tj) can be calculated using the following thermal equation:

$$Tj = W \times \{Rth(j - win)\} + Twin$$

where, the inlet coolant temperature T_{win} is represents the temperature at the position shown in Fig. 3-6. As shown in Fig. 3-6, the temperature at points other than the relevant point is measured low in actual state, and it depends on the heat dissipation performance of the water jacket. Please be designed to be aware of these.



W : Module power loss

T_j : Junction temperature if IGBT chip

T_{win} : Cooling water temperature

$Rth_{h(j-win)}$: Thermal resistance between junction and cooling water

Fig. 3-3 Thermal resistance equivalent circuit

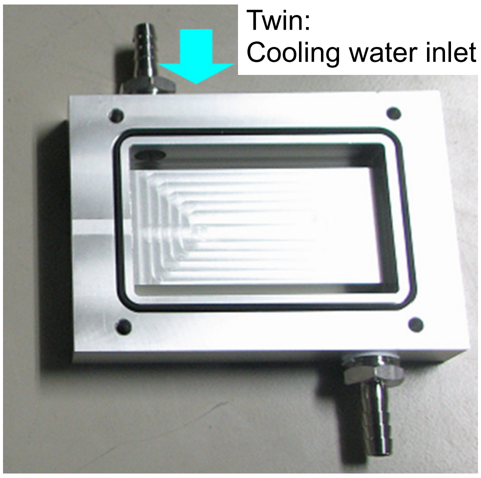


Fig. 3-4 Cooling water inlet temperature

2.2 Thermal equations for transient power loss calculations

Generally, it is enough to calculate Tj in steady state from the average loss calculated as described previous section. In actual situations, however, actual operation has temperature ripples as shown in Fig. 3-7 because repetitive switching produce pulse wave power dissipation and heat generation. In this case, considering the generated loss as a continuous rectangular-wave pulse having a certain cycle and a peak value, the temperature ripple peak value (Tjp) can be calculated approximately using a transit thermal resistance curve shown in the specification (Fig. 3-8).

$$Tjp - Twin = P \times \left[R(\infty) \times \frac{t1}{t2} + \left(1 - \frac{t1}{t2}\right) \times R(t1+t2) - R(t2) + R(t1) \right]$$

Select a water jacket by checking that this Tjp does not exceed Tjmax.

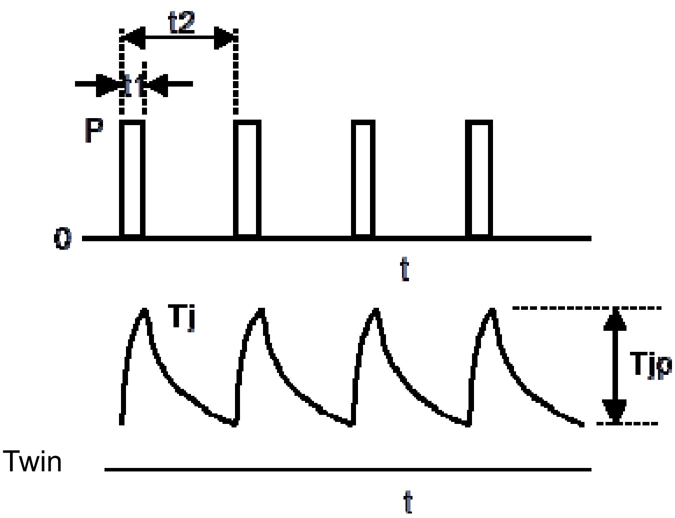


Fig. 3-5 Temperature ripple

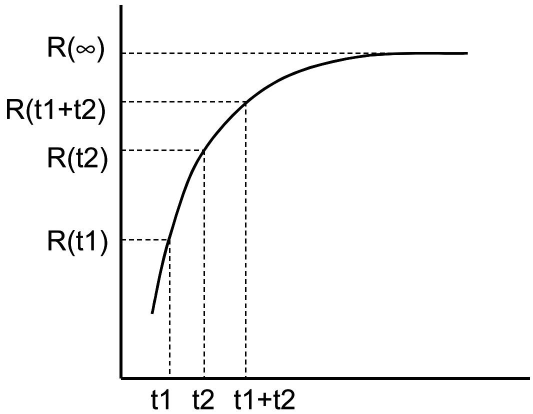


Fig. 3-6 Transit thermal resistance curve

3. Method of mounting the IGBT module

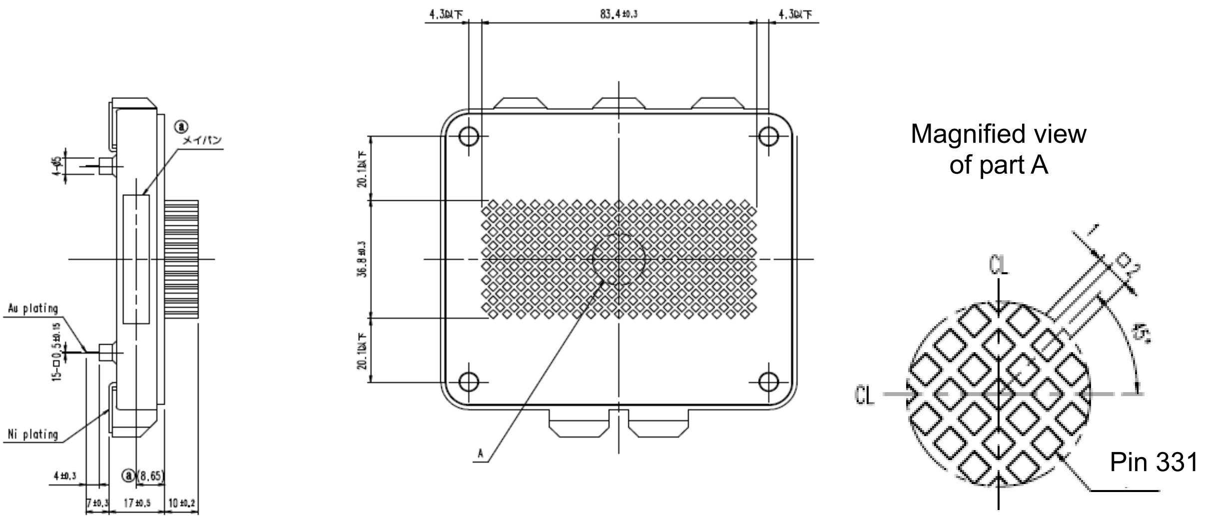
3.1 Method of mounting the module to the liquid-cooling jacket

By mounting the automotive IGBT module to a liquid-cooling jacket and directly cooling it with cooling water, the thermal resistance can be suppressed to lower than the conventional structure which IGBT module is mounted to a heat sink and cooled by air.

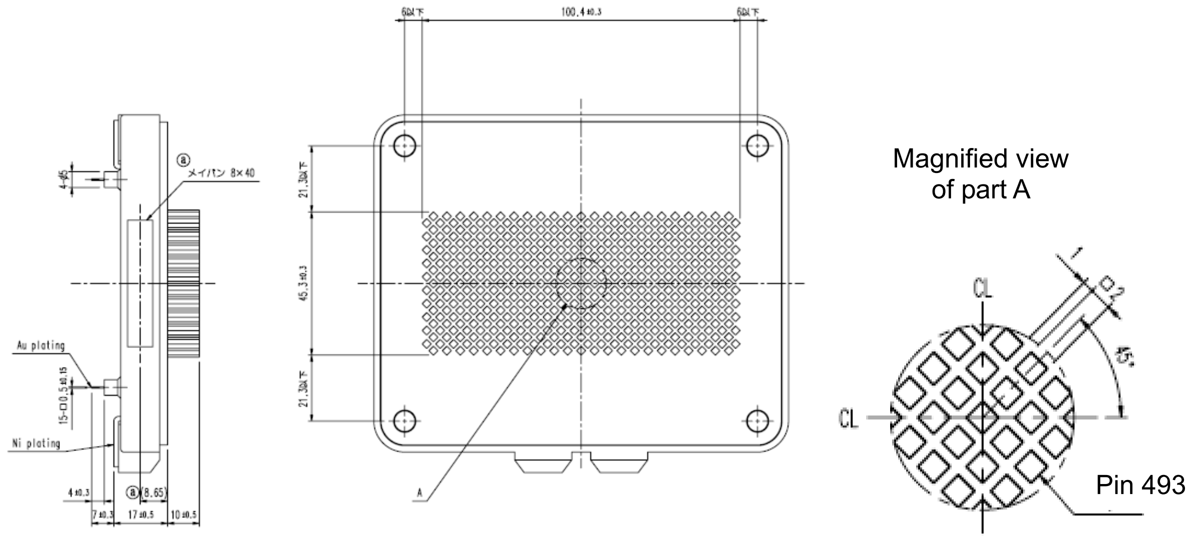
Figure 3-9 is the outline drawing of the module with pin-fin baseplate. The fin base is made of a nickel (Ni)-plated copper (Cu) material. Please make sure not to damage the nickel plating, pin-fins and surface of the base plate when mounting the module. Especially scratches on the base surface might cause a liquid leakage.

Please note following points when you design a liquid-cooling jacket:

- Flow path and pressure loss
- Selection of cooling liquid
- Clearance between the pin-fin and the cooling jacket
- Selection of O-ring



6MBI400VW-065V



6MBI600VW-065V

Fig. 3-7 Outline drawing of the fin

3.1.1 Flow path and pressure loss

The liquid-cooling jacket should be designed with attention to the flow path of coolant because the pressure loss and chip temperature are varied by the state of flow path. As shown in Fig. 3-10, if the coolant flows in a major (long) axis of the pin-fin area (Direction 1), the pressure loss is higher. Meanwhile, if the coolant flows in a minor (short) axis of the pin-fin area (Direction 2), the pressure loss is lower. Regarding chip temperature, the variation of chip temperature can be suppressed if the coolant is fed in Direction 2 rather than Direction 1.

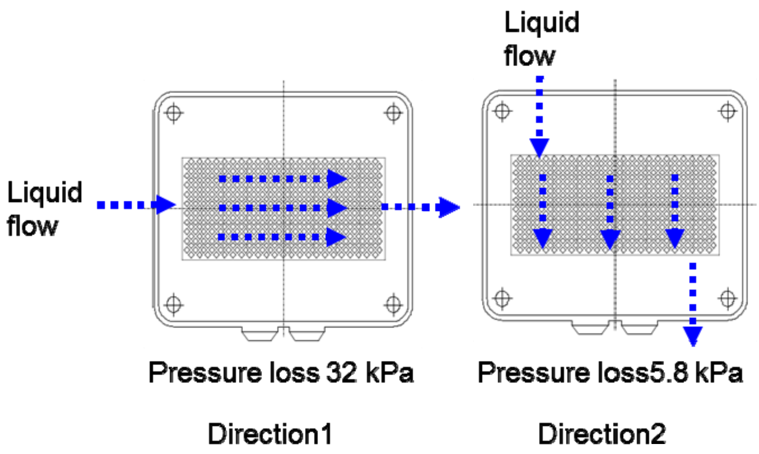


Fig. 3-8 Dependency of pressure loss on flow path

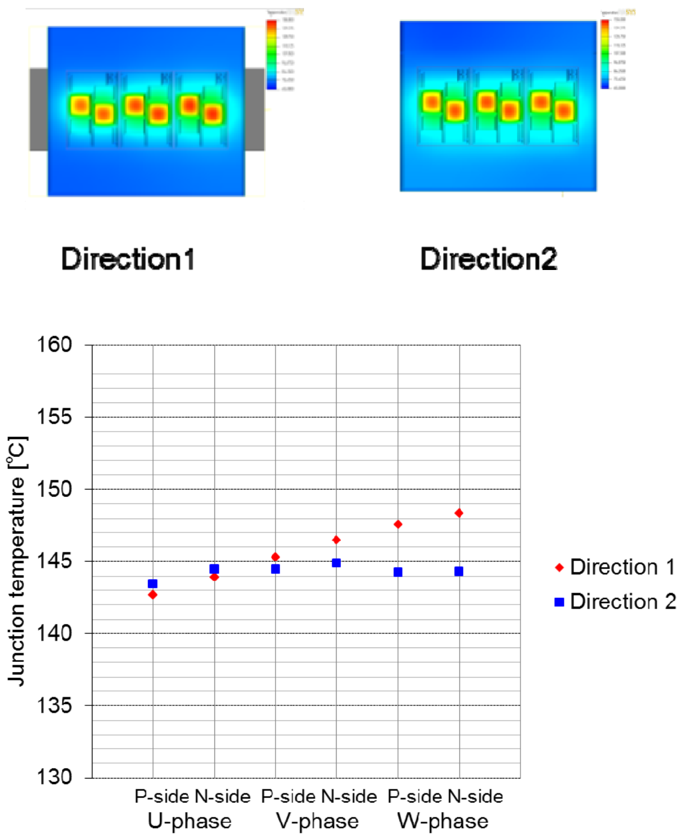


Fig. 3-9 Dependency of chip temperature on flow path

3.1.2 Selection of cooling liquid

A mixed liquid of water and ethylene glycol is a suitable coolant for the direct liquid-cooling system. As cooling liquid, 50% of long life coolant (LLC) aqueous solution is recommended. Impurities contained in the coolant cause a clogging of flow path, and increasing pressure loss and decreasing cooling performance. Please eliminate impurities as much as possible. In addition, if the pH value of the coolant is low, the nickel plating may be corroded. To prevent the corrosion of fin base of the IGBT module, it is recommended to monitor the pH buffer solution and the corrosion inhibitor in the coolant periodically to keep these concentrations over the value which recommended by the LLC manufacturer. Replenish or replace the pH buffer agent and the corrosion inhibitor before their concentration decreases to the recommended reference value or lower.

3.1.3 Clearance between the pin fin and the cooling jacket

Figure 3-12 shows the thermal resistance and pressure loss dependences on the gap between the tip of the pin-fin and the bottom of liquid-cooling jacket. If the gap becomes larger, the pressure loss is smaller. However, the thermal resistance becomes higher because the coolant flows through the gap unnecessarily. The recommended gap length is 0.5 mm.

If the gap between the side of the pin fin and the side wall of the cooling jacket is too large, the coolant flows unnecessarily flow path, thus decreasing cooling performance. Perform design so that the gap becomes as small as possible.

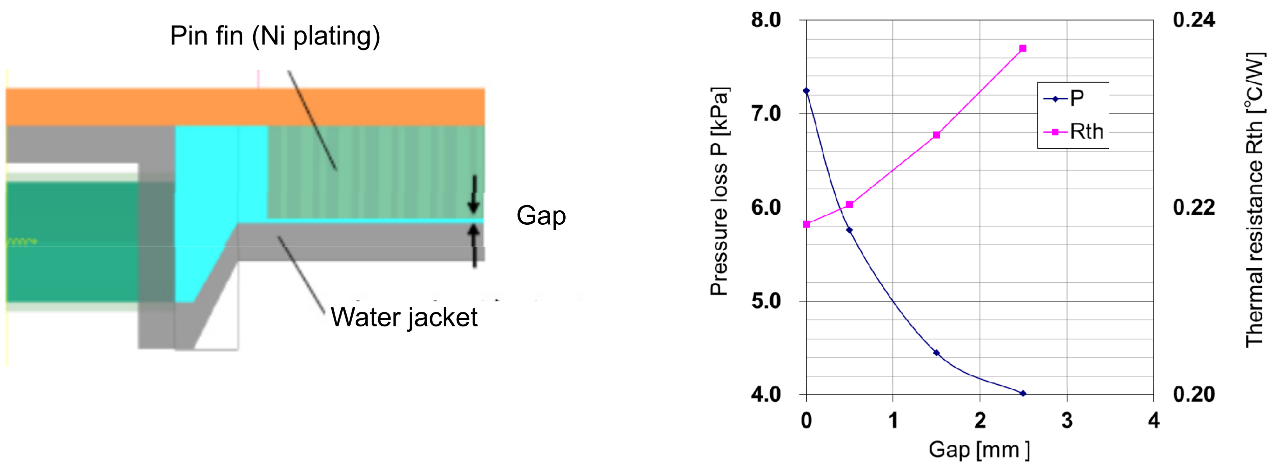


Fig. 3-10 Relation between the gap and pressure loss/thermal resistance

Figure 3-13 shows the relation between the pipe diameter of the inlet and outlet of coolant and the pressure loss when 50% LLC is fed at the flow rate of 10 L/min. If the pipe diameter is too small, the pressure loss increases. The recommended pipe diameter is ϕ12 mm.

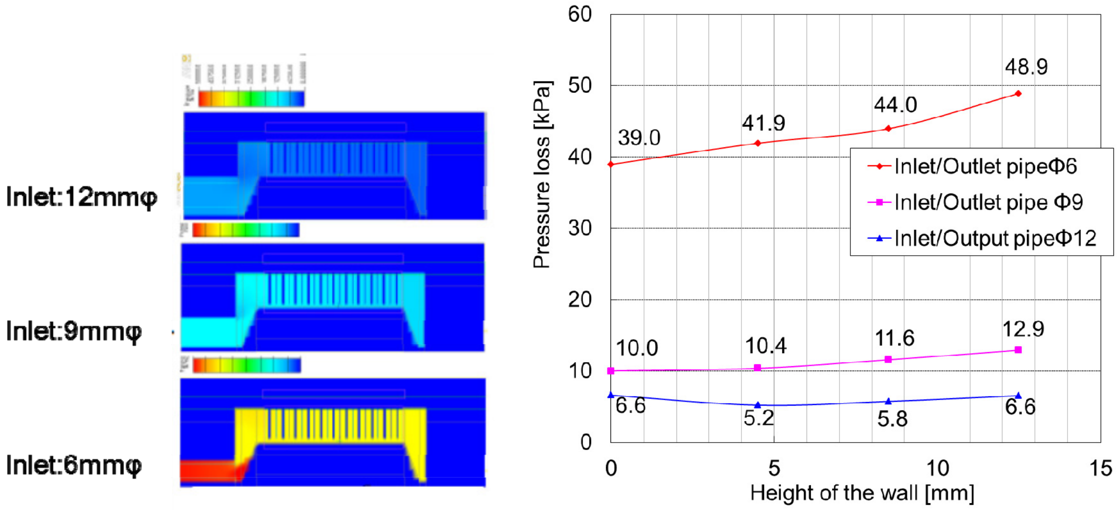


Fig. 3-11 Pipe diameter and pressure loss

3.1.4 Selection of O-ring

Since the IGBT module is mounted to the liquid-cooling jacket via a sealing material, sealing technique for preventing coolant leakage even if temperature and water pressure change is essential. As a sealing material, an O-ring that is mounted by grooving the liquid-cooling jacket is recommended. As the material of the sealing material, ethylene propylene rubber (E116, NOK Corporation) is recommended.

Figure 3-14 shows a typical sealing part. As the diameter of the sealing material, ϕ2.5 mm or larger is recommended. The groove of the water jacket to which the sealing material is to be mounted should be as deep as approximately 0.7 to 0.8 times the diameter of the sealing material. Ensure that the average surface roughness of the sealing surface of the water jacket falls within the following range: Ra<1.6 μm, Rz<6.3 μm.

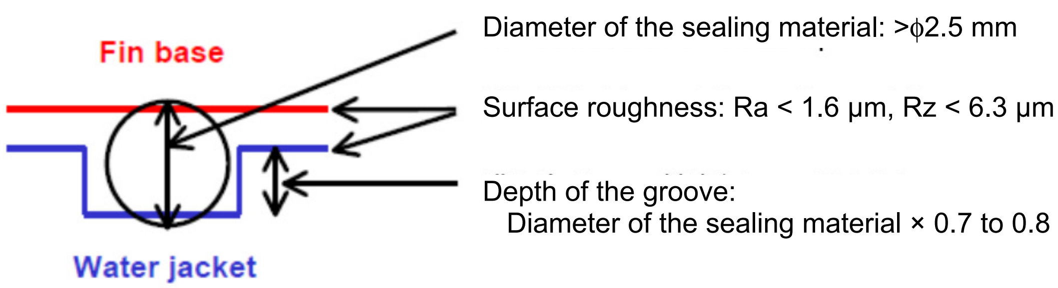


Fig. 3-12 Detailed drawing of the sealing part

3.1.5 Typical water jacket

Refer to figure 3-15(a) and (b) for an example of liquid-cooling jacket for 6MBI400VW-065V/ 6MBI600VW-065V.

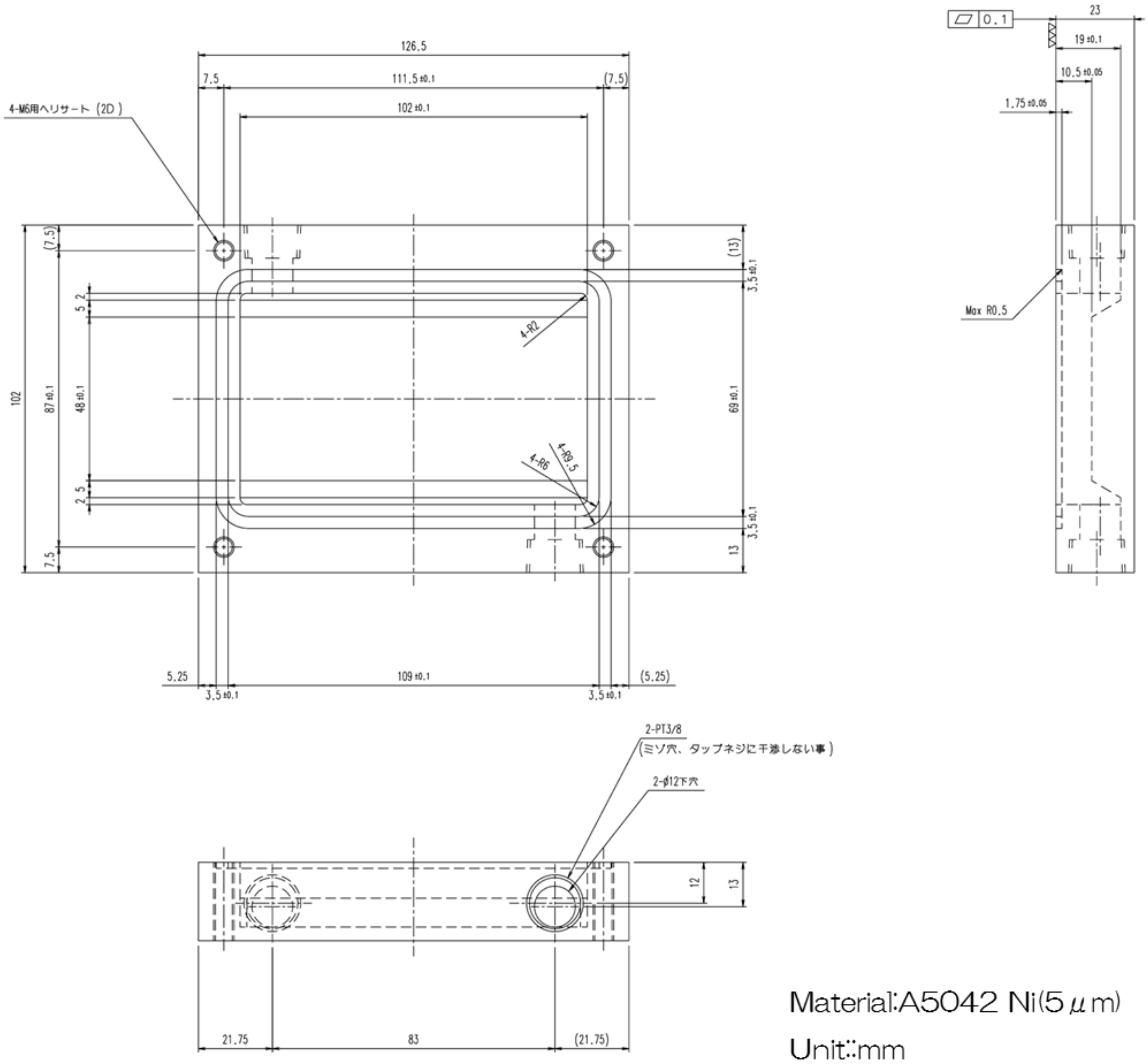


Fig. 3-15(a) liquid-cooling jacket for 6MB400VW-065V

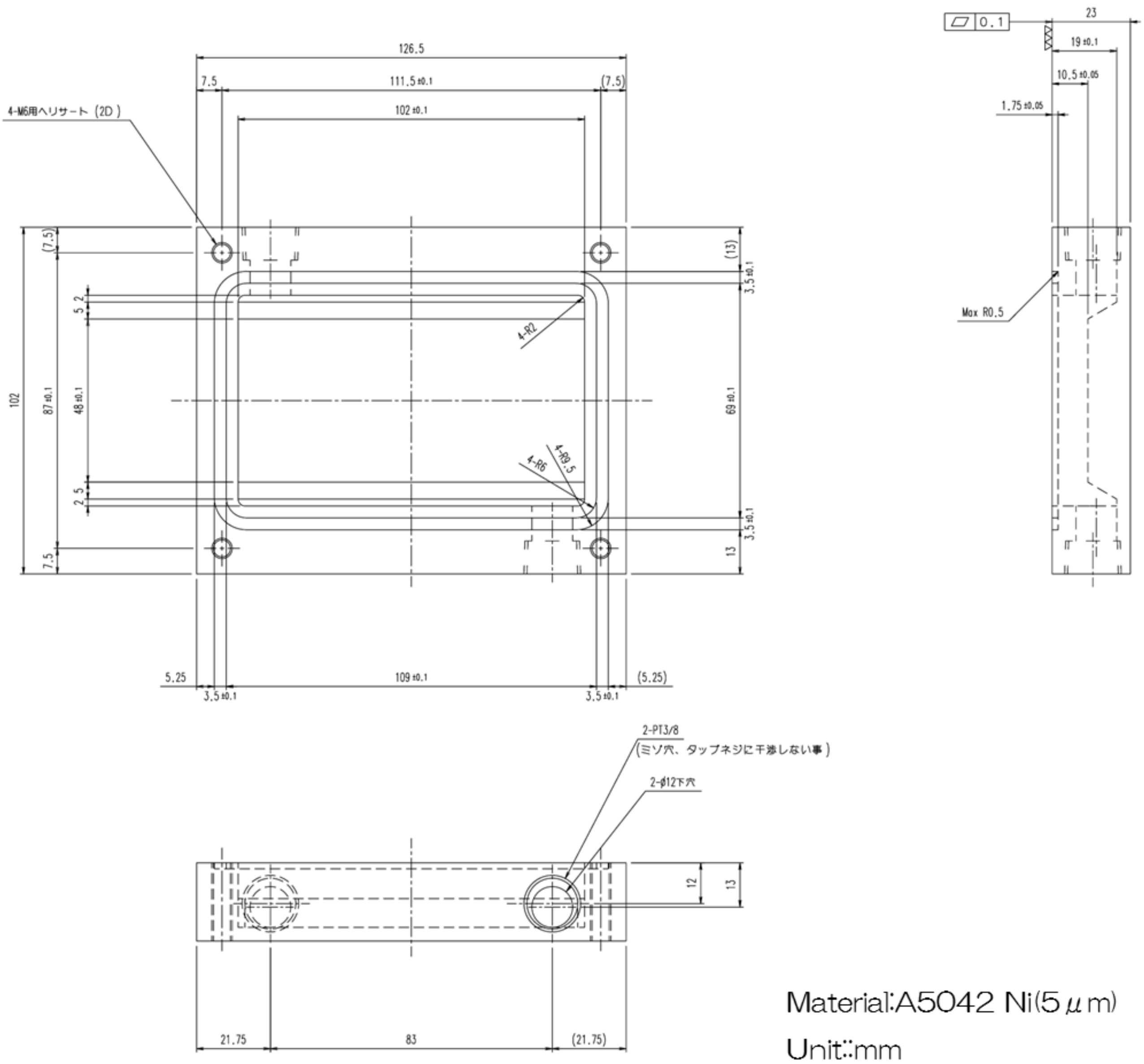
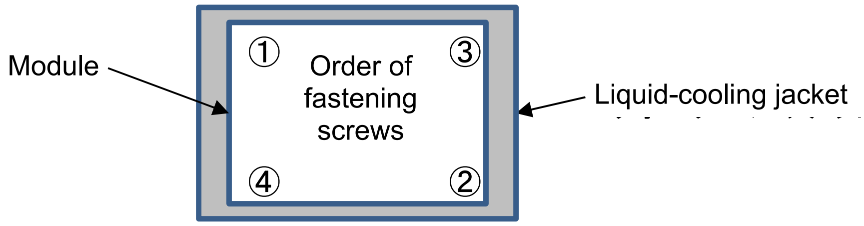


Fig. 3-15(b) liquid-cooling jacket for 6MB600VW-065V

3.2 Mounting procedure

Figure 3-16 shows the procedure of fastening screws when mounting the IGBT module on cooling jacket. The screws should be fastened by specified torque which is shown in the specification. If this torque is insufficient, it would cause a coolant leakage from the jacket or loosening of screws during operation. If excessive torque is applied, the case might be damaged.



	Torque	Sequence
Initial	1/3 specified torque	①→②→③→④
Final	Full specified torque	④→③→②→①

Fig. 3-16 Screw sequence for IGBT module

3.3 Temperature check

After selecting a liquid-cooling jacket and determining the mounting position of the IGBT module, the temperature of each part should be measured to make sure that the junction temperature (Tj) of the IGBT module does not exceed the rating or the designed value.