Chapter 3 Heat Dissipation Design Method

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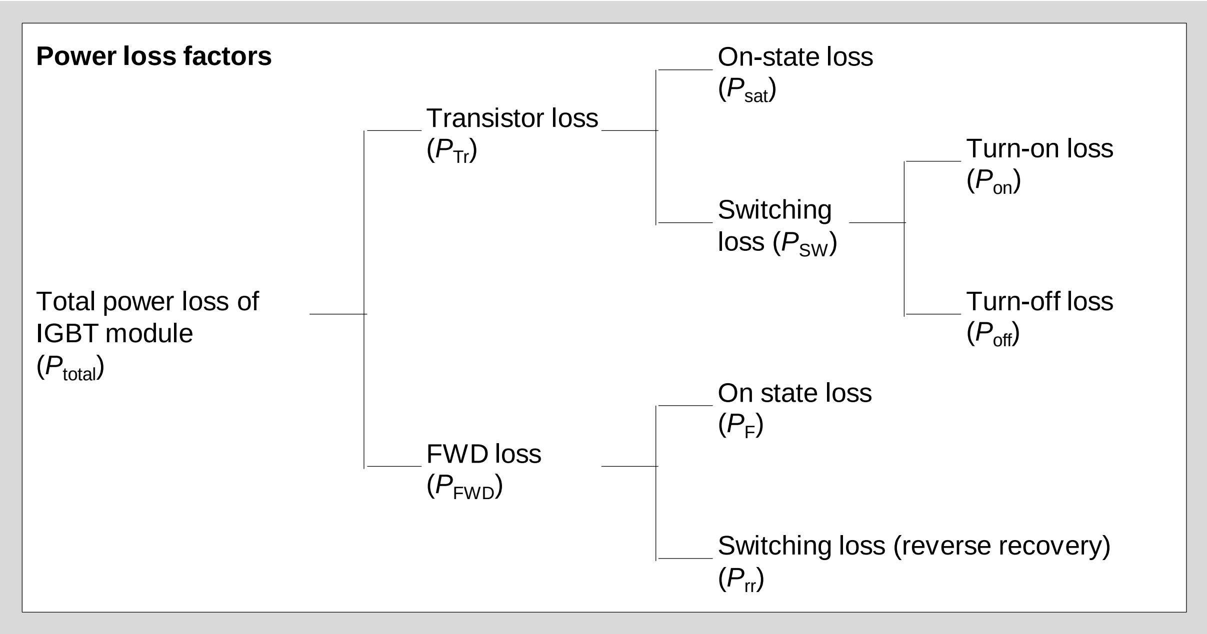
This chapter describes heat dissipation design.
To operate the IGBT safely, it is necessary not to allow the junction temperature (T_{vj}) to exceed $T_{vj(max)}$.
Perform thermal design with sufficient allowance in order not for $T_{vj(max)}$ to be exceeded not only in the operation under the rated 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.

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 part 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 T_{vj} below the maximum rated value.
The on-state voltage and switching loss values at higher junction temperature (T_{vj} = 175℃) 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

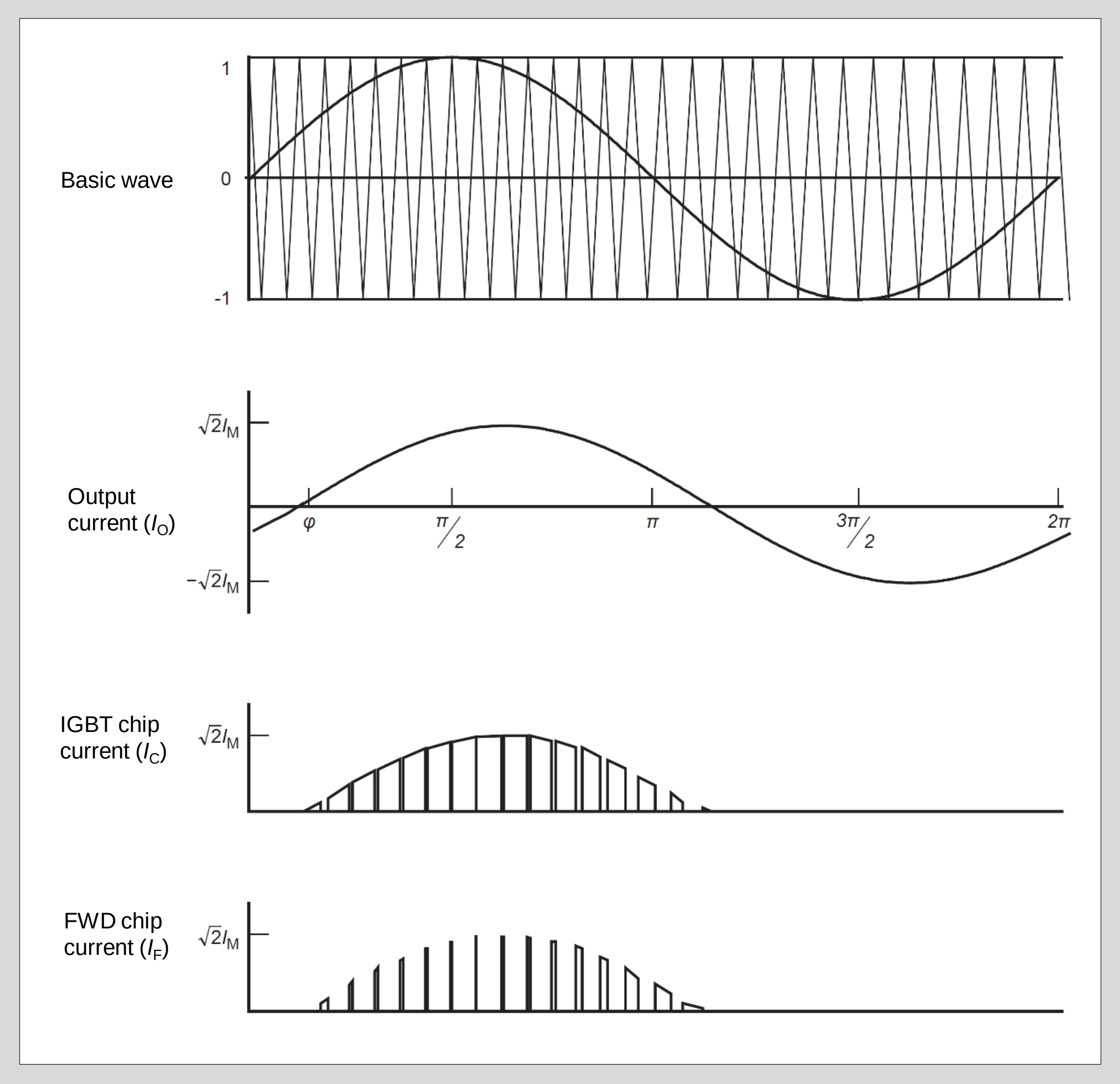


Fig. 3-1 PWM inverter output current

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 (P_{sat}, P_F)

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:

$$(P_{sat}) = DT\int_0^x I_C V_{CE(sat)} d\theta$$

$$= \frac{1}{2}DT\left[\frac{2\sqrt{2}}{\pi} I_M V_0 + I_M{}^2 R\right]$$

$$(P_F) = \frac{1}{2}DT\left[\frac{2\sqrt{2}}{\pi} I_M V_0 + I_M{}^2 R\right]$$

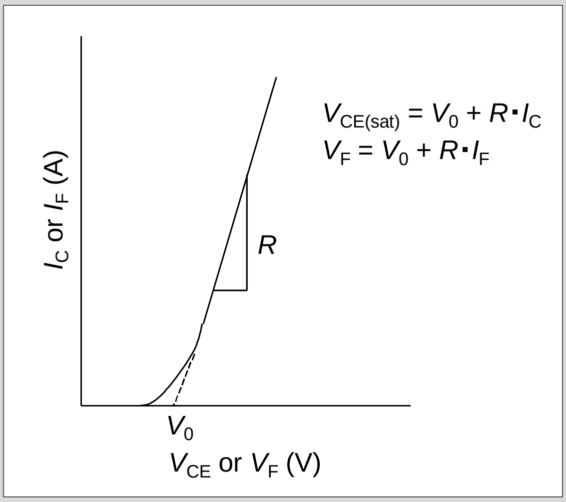


Fig. 3-2 Approximate output characteristic

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

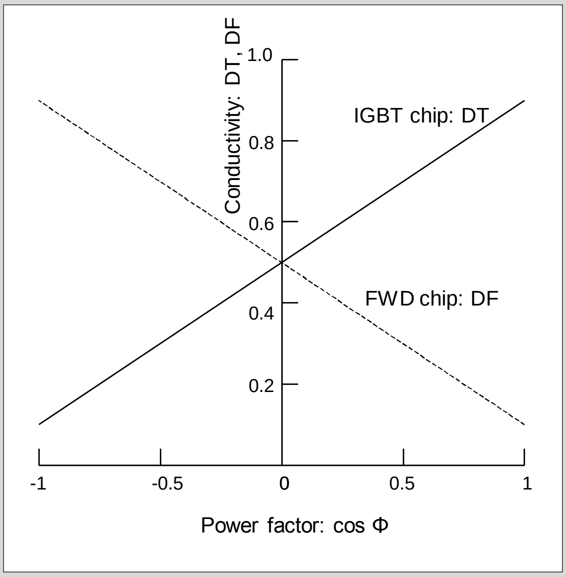


Fig. 3-3 Relationship between power factor sine-wave PWM inverter and conductivity

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

$$E_{on} = E_{on'}(I_C \,/\, \text{rated } I_C)^{a}$$

$$E_{off} = E_{off'}(I_C \,/\, \text{rated } I_C)^{b}$$

$$E_{rr} = E_{rr'}(I_C \,/\, \text{rated } I_C)^{c}$$

a, b, c: Multiplier

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

The switching losses can be represented as follows:

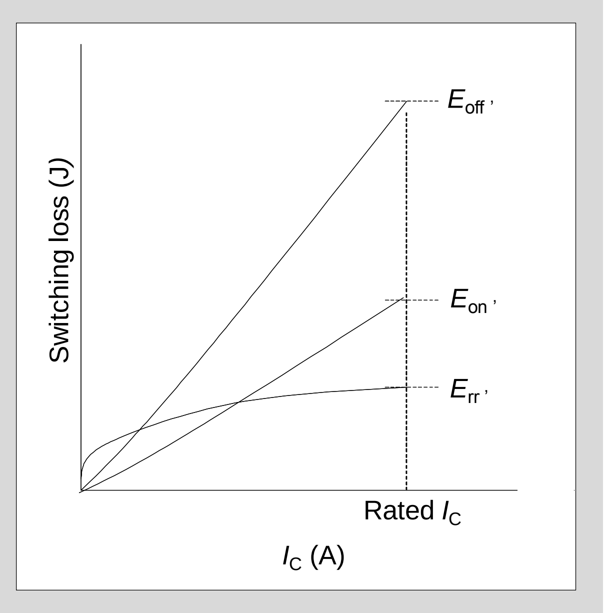


Fig. 3-4 Approximate switching losses

• Turn-on loss (P_{on})

$$P_{on} = f_o \sum_{k=1}^{n} (E_{on})k \qquad \left(\text{n: Half}-\text{cycle switing count} = \frac{f_C}{2f_O}\right)$$

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

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

$$= f_o E_{on'} \frac{1}{\text{rated } I_{C}{}^{a}} \text{n} I_{M}{}^{a}$$

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

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

$E_{on}(I_M)$: $I_C = E_{on}$ at I_M

• Turn-off loss (P_{off})

$$P_{\text{off}} = \frac{1}{2} f_{\text{C}} E_{\text{off}}(I_{\text{M}})$$

$E_{\text{off}}(I_{\text{M}})$: $I_{\text{C}} = E_{\text{off}}$ at I_{M}

• FWD reverse recovery loss (P_{rr})

$$P_{\text{rr}} \approx \frac{1}{2} f_{\text{C}}\, E_{\text{rr}}(I_{\text{M}})$$

$E_{\text{rr}}(I_{\text{M}})$: $I_{\text{C}} = E_{\text{rr}}$ at I_{M}

Total power loss
Using the results obtained in section 1.2.

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

FWD chip power loss: $P_{\text{FWD}} = P_{\text{F}} + P_{\text{rr}}$

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. Usage of the Cooler with Water Jacket

Usage of cooling system of this IGBT module is very easy, because a water jacket is already integrated to cooling fin base. So user do not need to design any water jacket comparing to conventional open pin fin type IGBT module.

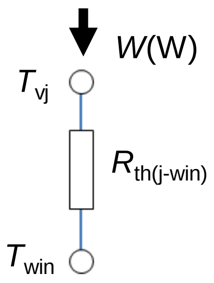
2.1 Thermal equation in steady state

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 (T_{vj}) can be calculated using the following thermal equation:

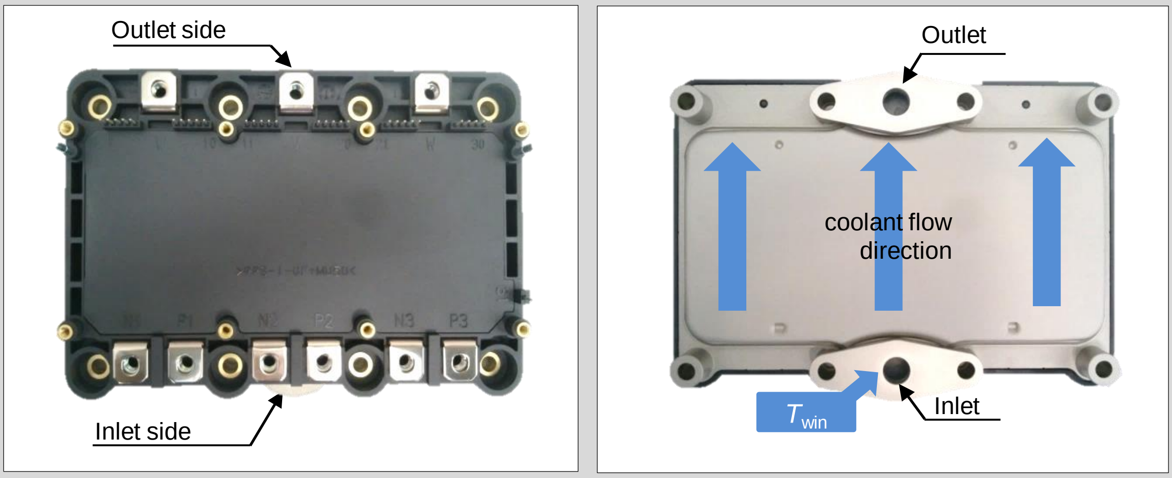
$$T_{vj} = W \times \{R_{th(j\text{-}win)}\} + T_{win}$$

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_{vj} : Junction temperature of IGBT chip
T_{win} : Cooling water temperature
$R_{th(j\text{-}win)}$: Thermal resistance between junction and cooling water

Fig. 3-5 Equivalent circuit of the thermal resistance



(a) Top view

(b) bottom view

Fig. 3-6 An inlet and an outlet of the cooling system and the coolant flow direction

2.2 Thermal equations for transient power loss calculations

Generally, it is enough to calculate T_{vj} 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 (T_{vjp}) can be calculated approximately using a transit thermal resistance curve shown in the specification (Fig. 3-8).

$$T_{vjp} - T_{win} = P \times \left[R(\infty) \times \frac{t_1}{t_2} + \left(1 - \frac{t_1}{t_2}\right) \times R(t_1 + t_2) - R(t_2) + R(t_1) \right]$$

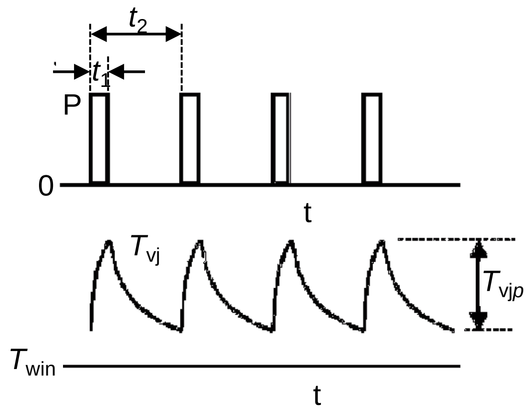


Fig. 3-7 Temperature ripple

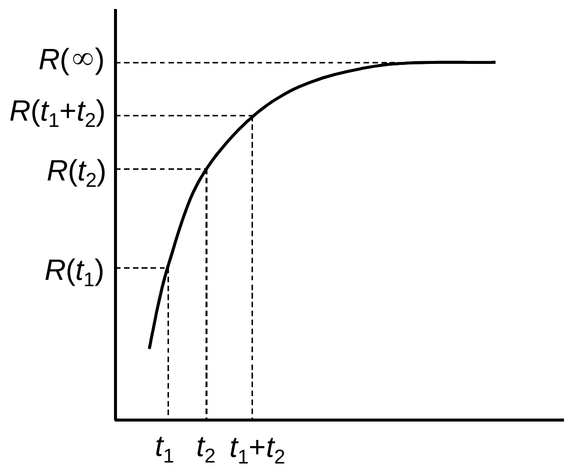


Fig. 3-8 Transit thermal resistance curve

2.3 Flow path and pressure loss

As shown in Fig. 3-6, the direction of cooling water is already designed from inlet to outlet. The pressure loss is almost same, even if the water flow direction were exchanged respectively. However, the water flow direction shall not be exchanged for safety operation, because the location of the junction temperature sensor diode is already fixed to the outlet side of the designed water flow direction.

2.4 Selection of cooling liquid

A mixed liquid of water and ethylene glycol shall be used as a coolant for the direct liquid-cooling system. As cooling liquid, 50% of long life coolant (LLC) aqueous solution is strongly recommended. Impurities contained in the coolant cause a clogging of flow path, and increasing pressure loss and decreasing cooling performance. So eliminating impurities shall be required to avoid performance degradation of the module. In addition, if water which corrosion inhibitor is not including is used, corrosion of aluminum oxide may be produced. 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.

IGBT module operation without coolant shall strictly forbid.

And any particle in the coolant which clog cooling system also shall be eliminated out by a filter.

2.5 Selection of O-ring

When this IGBT is installed to a power control system, certain suitable O-ring is needed. Size and material of O-ring depend on the system design and the operational environment of the system. Therefore, when O-ring is selected, sufficient confirmation about seal performance shall be needed.

There is an example of O-ring in Table 3-1 as the flange adapter kit for IGBT module evaluation.

Seal area of the flange for the flange adapter kit is shown in Fig. 3-9.

2.6 Temperature check

After selecting a O-ring and determining the mounting position of the IGBT module, the temperature of each part should be measured to make sure that the junction temperature (T_{vj}) of the IGBT module does not exceed the rating or the designed value.

3. Flange Adaptor Kit

Flange adaptor kit is prepared as an optional part.
The kit is including a sealing block with O-ring and a nipple to connect the cooler to the water line.

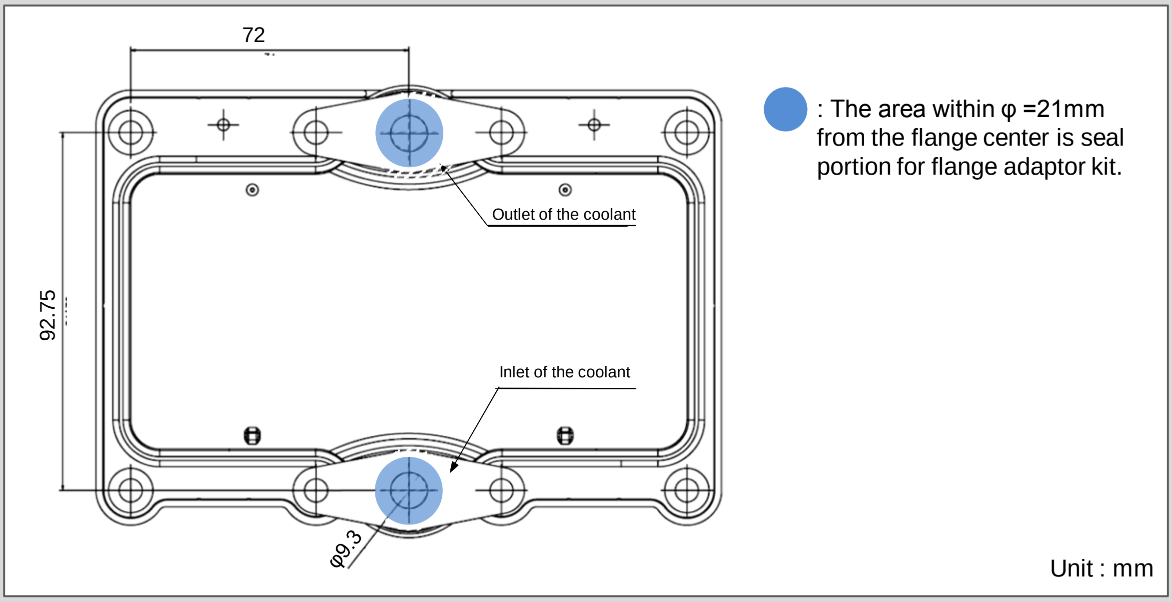
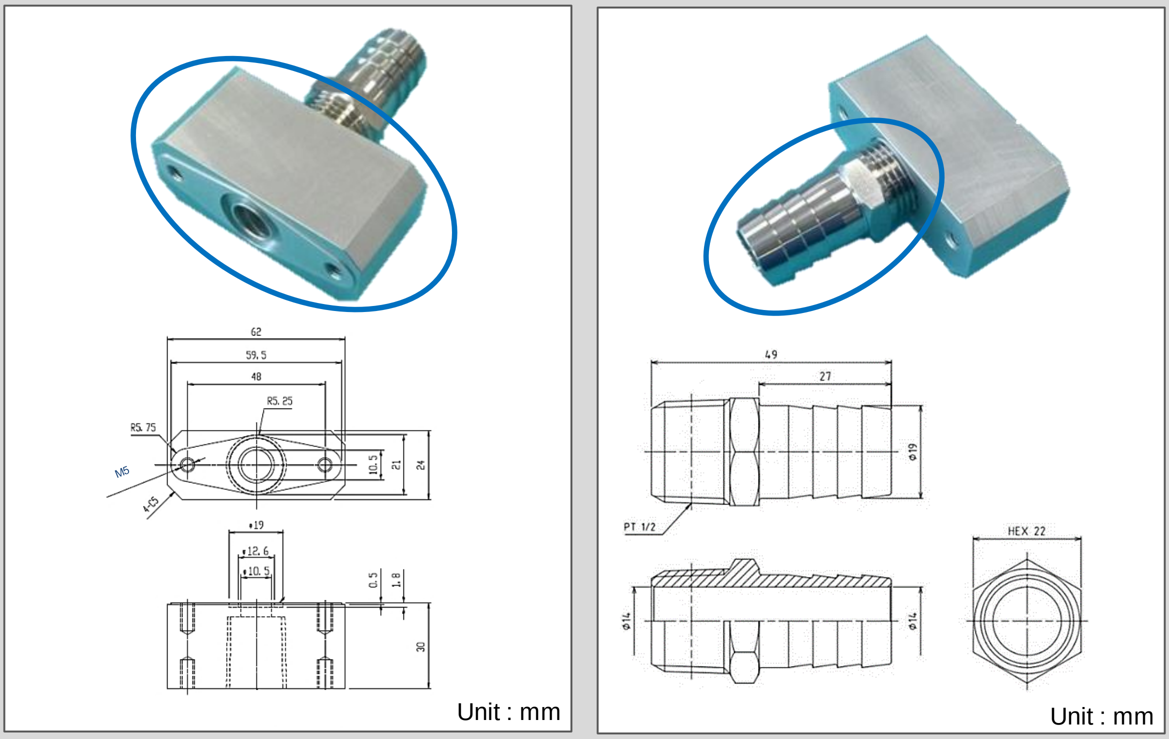


Fig. 3-9 Seal area of the flange



(a) Flange adaptor base

(b) Nipple of flange adaptor

Fig. 3-10 Flange adaptor kit : flange adaptor base and nipple

Reference information of O-ring of the flange adaptor kit

- Size : P15 @JIS standard
- Material : NBR(Nitrile rubber)
- Hardness : 70

Table 3-1 Size of O-ring (Unit : mm)

Nominal size (JIS)	Dimension of O-ring			Dimension of grove						
	Thickness W	Inner dimension do		d	D	G(tolerance $^{+0.25}_{0}$)			H	R
						No Backup ring	One backup ring	Two backup ring	H±0.05	MAX
P10A		9.8	±0.20	10	14					
P11		10.8	±0.21	11	15					
P11.2		11.0		11.2	15.2					
P12		11.8		12	16					
P12.5		12.3	±0.22	12.5	16.5					
P14		13.8		14	18					
P15	2.4±0.09	14.8	±0.24	$15^{0}_{-0.06}$	$19^{+0.06}_{0}$	3.2	4.4	6.0	1.8	0.4
P16		15.8		16	20					
P18		17.8	±0.25	18	22					
P20		19.8	±0.26	20	24					
P21		20.8	±0.27	21	25					
P22		21.8	±0.28	22	26					

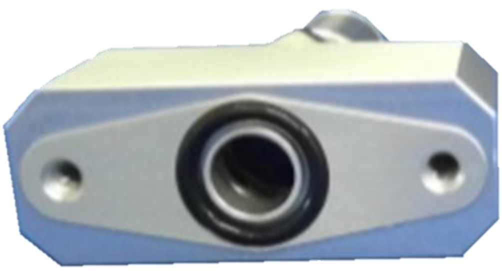


Fig. 3-11 The image of assembled O-ring onto the flange adaptor base