Temperature Dependency of The On-state Voltage of IGBT And Its Application in Thermal Resistance Test

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***Abstract*—In this paper, the temperature dependency of the on-state voltage of insulated-gate bipolar transistor is analyzed with an emphasis on the influence of collector current. The small-current on-state voltage has a negative temperature coefficient while the large-current on-state voltage has a positive temperature coefficient. Based on the analysis, two thermal resistance test systems supplying the small heating current and large heating current respectively were built and compared. To assure the reliability and accuracy, large-current thermal resistance test system is preferred.**

Keywords—insulated-gate bipolar transistor; on-state voltage; thermal resistance; collector current

I. Introduction

Thermal resistance test is commonly implemented to evaluate the performance of power device packages or cooling systems. There are mainly two different thermal resistance test methods, electrical test method[1] and dual interface test method[2].

A typical thermal-resistance test system for insulated-gate bipolar transistor(IGBT) is shown in Fig.1[3]. During the test, the device under test (DUT) is kept in on state and the on-state voltage at sensing current (I_m, 10~100mA) is used to be the indicator of device junction temperature[4]. Heating current (I_P, 10~1000A) is applied to cause the junction temperature to rise. The switch can be made up by multiple IGBTs or metal-oxide-semiconductor field-effect transistors (MOSFETs) with large rated current. The cooling system consisting of a reservoir, pump, radiator and cold plate is utilized to dissipate the heat for the switch and to control the case temperature of the DUT.

The procedure of the junction-to-case thermal resistance (R_{thJC}) test based on the electrical test method is as follows. First, the I_P is disconnected. The on-state voltage V_{ce0} and initial case temperature T_{C0} are recorded. Then the I_P is applied to the DUT to heat up the device. Once the thermal steady-state has been reached, the heating voltage V_P and DUT case temperature T_{C1} are recorded, and then the I_P is switched off completely. The temperature equilibrium is defined as not more than 0.5°C change during a five minutes interval. Measuring the voltage V_{ce1} right after the disconnection of I_P.

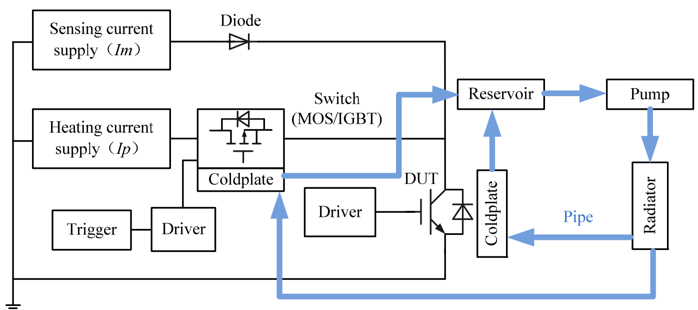

Fig.1. Thermal resistance test system

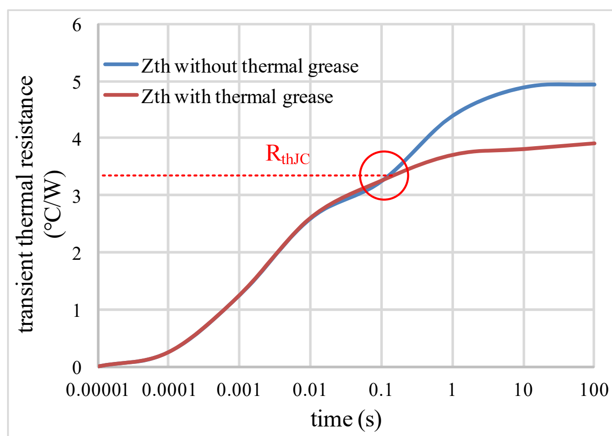

Fig.2. Transient thermal resistance curves in cooling stage

The junction-to-case thermal resistance is calculated as (1)~(3).

$$T_J = T_{C0} + K \cdot |V_{ce0} - V_{ce1}| \quad (1)$$

$$T_C = T_{C1} \quad (2)$$

$$R_{thJC} = \frac{T_J - T_C}{V_P I_P} \quad (3)$$

The procedure of the dual interface test method is as follows. The DUT is fixed onto a heat sink directly. First, the I_P is disconnected. The on-state voltage V_{ce0} and initial case

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temperature T_{C0} are recorded. Then the I_P is applied to heat up the DUT until the temperature equilibrium is reached. Disconnect I_P and record the $V_{ce1}(t)$ curve in the cooling stage. Paint thermal grease between the DUT and heat sink and repeat the above steps, so another cooling curve $V_{ce2}(t)$ is obtained. Two different transient thermal resistance curves can be drawn using (4)~(6), shown in Fig.2. The transient thermal resistance at the separation point of these two curves is the R_{thJC}.

$$T_J(t) = T_{C0} + K \cdot |V_{ce0} - V_{ce}(t)| \tag{4}$$

$$T_{J0} = T_{C0} \tag{5}$$

$$Z_{thJC}(t) = \frac{T_J(t) - T_{J0}}{V_P I_P} \tag{6}$$

According to the above description, one of the key steps in the thermal resistance test is the heating of the DUT. There are two methods to supply the heating power. One method is to supply small heating current and large heating voltage and the other method is to supply large heating current and small heating voltage. Although the same power is applied to the DUT, different performance of the DUT can be observed because of the influence of current on the temperature dependency of on-state voltage of IGBT.

In this paper, the temperature dependency of the on-state voltage of IGBT is analyzed with an emphasis on the influence of collector current. Based on the analysis, two thermal resistance test systems supplying the small heating current and large heating current respectively were built and compared. To assure the reliability and accuracy, large-current thermal resistance test system is preferred.

II. Temperature Dependency of The On-state Voltage

A. Theoretical Analysis

Fig.3 illustrates the structure of the n-channel planar non-punch-through IGBT[5]. The on-state voltage of IGBT consists of collector-base junction voltage, base-region voltage, MOS-channel voltage and series-resistor voltage. The on-state voltage can be obtained as (7)[6]. Parameters definitions and their temperature characteristics are concluded in Table I[7].

$$V_{ce(on)} = \frac{2kT}{q}\ln\left(\frac{2Q}{qAWn_i}\right) + \frac{I_T W}{(1+1/b)u_n Aqn_{eff}} - \frac{D}{u_n}\ln\left(\frac{2Q/qAW + N_B}{N_B}\right) + I_n \frac{1}{K_p(V_{gs} - V_T)} + I_T R_S \tag{7}$$

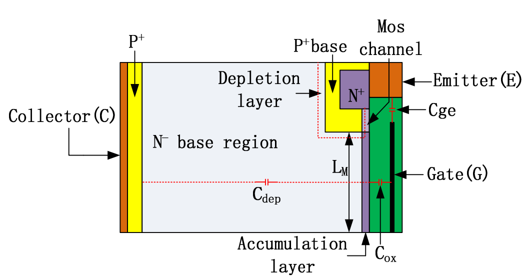

Fig.3. Structure of the n-channel planar IGBT in on-state

TABLE I. Parameters Definitions And Characteristics

Parameters	Definitions	Temperature Characteristics	
T	Absolute temperature (K)		↑
k	Boltzmann constant (J/K)	1.38E-23	→
q	Electronic charge (C)	1.6E-19	→
Q	Total excess carrier base charge (C)	1.0E-6~1.0E-1	→
A	Active area (cm^2)	0.1~3	→
W	Quasi-neutral base width (um)	30~90	→
n_i	Intrinsic carrier concentration (cm^{-3})	$n_i = CT^{1.5}e^{-\frac{Eg(0)}{2kT}}$	↑
V_T	MOS channel threshold voltage (V)	$V_T = V_{T0}\text{-}9.65e^{-3} \bullet (T - T_0)$	↓
I_T	Total collector current (A)		→
b	Ambipolar mobility ratio	3	→
u_n	Electron mobility (cm^2/(Vs))	$u_n = u_{n0}(T_0/T)^{2.5}$	↓
n_{eff}	Effective electro carrier concentration in the base region (cm^{-3})	3.4E15~3.4E20	→
D	Ambipolar diffusivity (cm^2/s)	$D = 2\frac{u_{n0}u_{p0}}{u_{n0}+u_{p0}} \bullet \frac{kT_0}{qT^{1.5}}$	↓
N_B	Base doping concentration (cm^{-3})	3.0E14	→
I_n	Electron current (A)	$I_n = I_T / 2.2$	→
K_p	MOS channel transconductance (A/V^2)	$K_P = K_{P0} \bullet (\frac{T_0}{T})^{0.8}$	↓
R_S	Device series resistance (Ω)		→

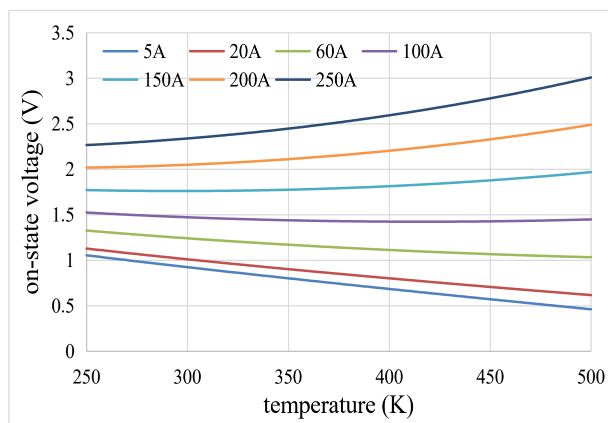

Fig.4. Temperature dependency of the on-state voltage

Substituting the parameters temperature characteristics into the (7), the on-state voltage temperature dependency can be obtained. Fig.4 shows the results at different collector current. The same parameters values as the ones in [6] were used in the calculation. It's obvious that the small-current on-state voltage has a negative temperature coefficient while the large-current on-state voltage has a positive temperature coefficient.

B. Experimental Verification

IGBT chip IKW40N120T2 (IKW) from Infineon was chosen to verify the analysis. Conventional double pulse test circuit was utilized and the load inductor was replaced by the resistor so that the collector current could be adjusted flexibly through the load resistance. To avoid the influence of self-heating, only one pulse was applied and the pulse width was 60us each time. Before each test, the IKW was heated for 1 hour to make sure that the thermal steady-state had been reached.

It is difficult to measure the on-state voltage directly because of the large dynamic range in the off- and on-states. Narrowing the dynamic range through the voltage clamping is the basic technique to overcome the problem. The clamping circuit in Fig.5 was implemented to measure the on-state voltage[8]. A typical test waveform was shown in Fig.6.

Fig.7 concludes the experimental results, which correspond to the analysis.

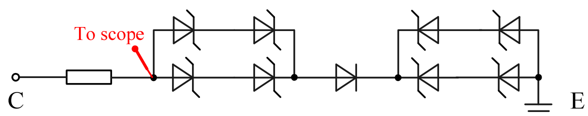

Fig.5. On-state voltage measurement circuit

Fig.6. On-state voltage measurement waveforms (400V/40A)

yellow-Vge, green-clamped Vce, indigo-original Vce, purple-current

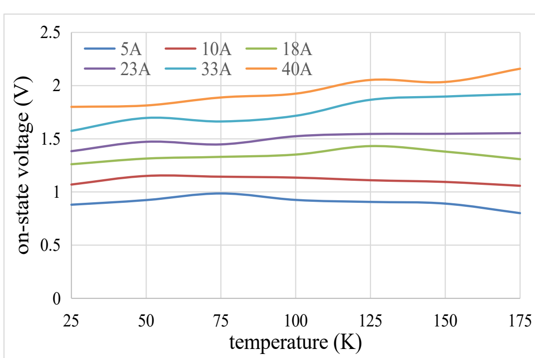

Fig.7. Experimental results

III. Thermal Resistance Test Systems

In the thermal resistance test, it’s a key step to heat up the DUT. The same heating power can be obtained by the large heating voltage and relatively small heating current or the reverse. Although the same power is applied to the DUT, different performance of the DUT can be observed.

A. Structure of Test Systems

Fig.8 displays the small-current thermal resistance test system. The heating current supply is a 30V/60A constant current source. The switch is a single MOSFET RU6199 from RuiChips. The sensing current supply clamping diode is MUR6020. Because the maximum current is only 60A, the 20mm^2 wire is enough to transfer the heating energy.

Fig.9 demonstrates the large-current thermal resistance test system. The heating current supply consists of three 15V/500A constant current sources. The switches include three IGBT modules FF1400R17IP4 from Infineon. Each switch controls one current source. The heating current can be as large as 1500A, so the wires with large dimensions should be used. The DUT cooling system dissipates the heat for DUT and controls the case temperature of DUT. There is also large heat generated in switches, so the switch cooling system is also implemented.

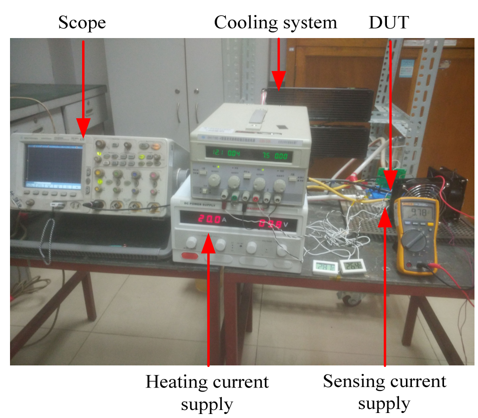

Fig.8. Small-current thermal resistance test system

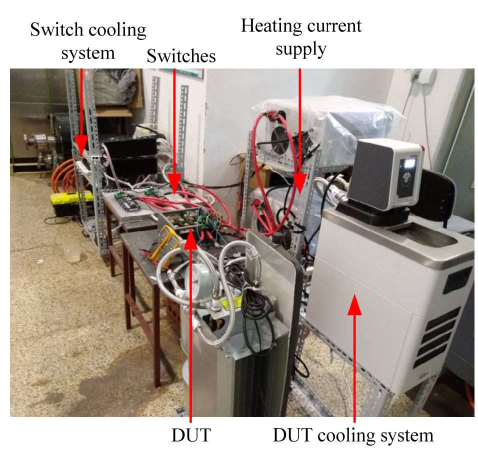

Fig.9. Large-current thermal resistance test system

B. Comparasion of The Test Systems

To compare the effects of the thermal resistance test systems, a 1200V/600A three-phase full bridge IGBT module was fabricated and used as the DUT. As shown in Fig.10, there are three parallel IGBT chips in each arm and there is no silicone gel above the chips. The module was painted to be black so that the junction temperature of the IGBT chips could be acquired by Infrared camera (IR).

The coolant temperature was set to be 35°C. When utilizing the small-current thermal resistance test system, to supply enough heating power, the gate voltage of DUT was reduced to be about 7.5V so that the heating voltage could be large. As for large-current thermal resistance test system, the gate voltage of DUT was 15V because the heating current could be very large. Fig.11 and Fig.12 display some experimental IR images of the parallel chips 1, 2 and 3 in Fig.10.

Comparing the images, when the small heating current is applied, there is large junction temperature imbalance among the parallel chips and the maximum junction temperature has reached more than 90°C even though the heating power is far smaller than the large heating current occasion. Because the junction temperature estimation method based on on-state voltage can only get the average junction temperature[9], the thermal resistance test becomes meaningless if the large junction temperature imbalance exists. Therefore, to assure the reliability and accuracy, large-current thermal resistance test system is preferred, especially for power module test where there are parallel chips.

For the discrete IGBTs, there is only one chip inside the package and the small-current thermal resistance system may also be suitable. However, more attention should be paid to the noise in gate driver because any small change in gate voltage may increase the heating loss largely and destroy the DUT.

IV. Application of The Large-current Thermal Resistance Test System

Supplying the same power loss and cooling conditions, the power module performance can be fully evaluated based on the large-current thermal resistance test system.

Fig.13 illustrates a 650V/400A three-phase full bridge SiC MOSFET module from StarPower. There is not any useful electrical parameter for the junction temperature estimation of SiC MOSFET by far, so the heating current was applied to the freewheeling diodes and the voltage drop of the freewheeling diode at sensing current was utilized as the temperature sensitive parameter.

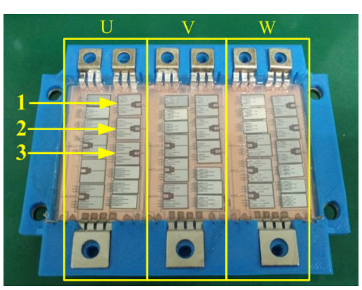

Fig.10. 1200V/600A three-phase full bridge IGBT module

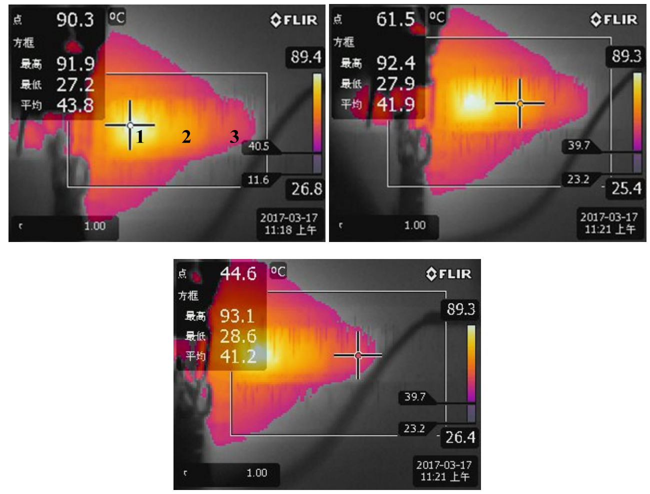

Fig.11. Junction temperature of three parallel chips

(I_P = 20A, V_P = 7.48V, H_P = 149.6W)

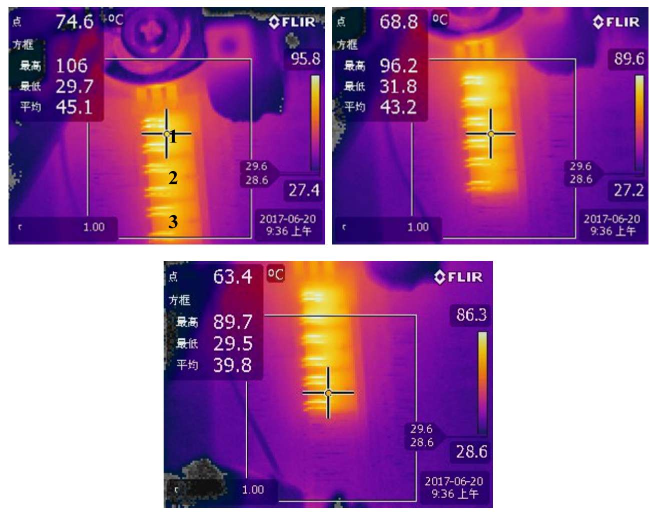

Fig.12. Junction temperature of three parallel chips

(I_P = 200A, V_P = 1.437V, H_P = 287.4W)

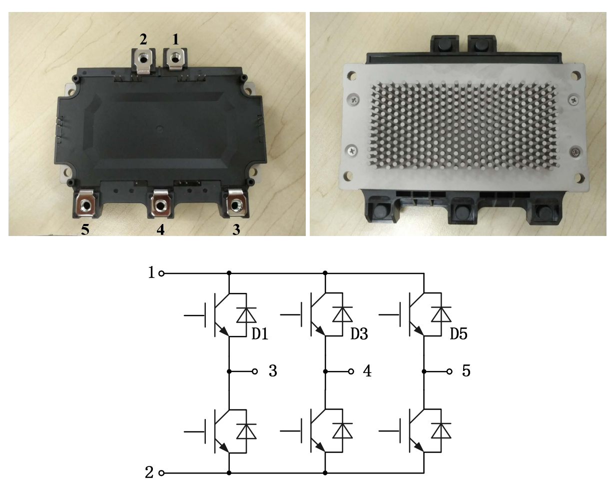

Fig.13. 650V/400A three-phase full bridge SiC MOSFET module

A. Thermal Resistance Test

The sensing current was 50mA, and the temperature sensitivity of the diode voltage drop is -1.86mV/℃. The DUT cooling system coolant temperature was remained to be 25℃, and the initial diode voltage drop was 820mV. The heating current was applied to the six freewheeling diodes through the BUS pins until the thermal equivalent was reached. Recorded the diode voltage drop right after the disconnection of the heating current, the temperature rise and thermal resistance of the diodes could be acquired. Table II displays the experimental conditions, and the results are demonstrated in Fig.14~Fig.16.

According to the results, the freewheeling diode junction temperature increases linearly as the power loss rising. The gradient of the line is the steady-state thermal resistance, which is 0.322℃/W, 0.314℃/W and 0.336℃/W for the D1, D3 and D5 respectively.

B. Influence of The Coolant Temperature

In the real cooling systems, different coolant temperature may be applied. If the coolant temperature has no influence on thermal resistance, it will be very simple to calculate the junction temperature by just compensating the coolant temperature variation.

Fig.17 displays the D5 temperature rise at different coolant temperature. It's obvious that the thermal resistance is independent on the coolant temperature.

V. CONCLUSION

In this paper, the temperature dependency of the on-state voltage of the non-punch-through IGBT is analyzed. The small-current on-state voltage has a negative temperature coefficient while the large-current on-state voltage has a positive temperature coefficient. Based on the analysis, two thermal resistance test systems were built and compared. If the small heating current is applied, there will be large junction temperature imbalance among the parallel chips and power device can be easily destroyed. To assure the reliability and accuracy, large-current thermal resistance test system is preferred. For the discrete IGBTs, small-current thermal resistance test system may also be suitable, but the gate voltage should be controlled very carefully to avoid the device failure. Based on the large-current thermal resistance test system, the power module working conditions can be idealy simulated and the performance can be fully evaluated, which can be a main step before utilizing the power module in real converters.

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TABLE II. EXPERIMENTAL CONDITIONS

Heating Current (A)	Heating Voltage (V)	D1 Loss (W)	D3 Loss (W)	D5 Loss (W)
150	2.132	46.00	45.95	45.80
270	2.387	83.11	83.11	83.11
390	2.630	120.51	121.74	120.25
570	3.100	188.67	189.14	186.20
690	3.540	251.62	247.48	248.40
750	3.724	280.00	280.00	278.00
810	4.049	325.35	324.95	327.91

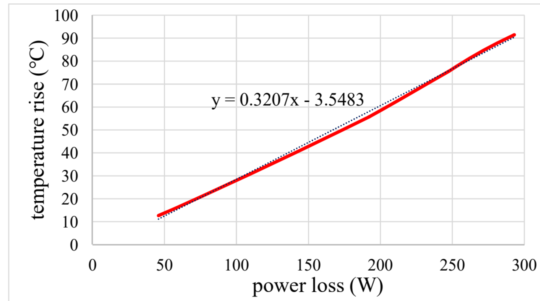

Fig.14. D1 temperature rise at different power loss

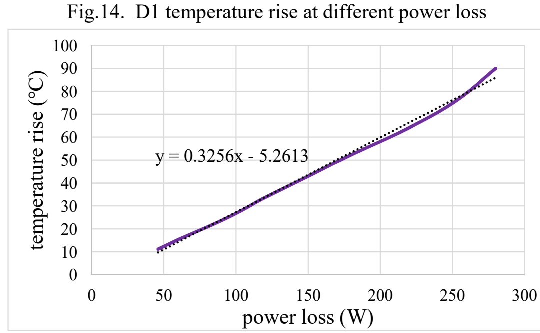

Fig.15. D3 temperature rise at different power loss

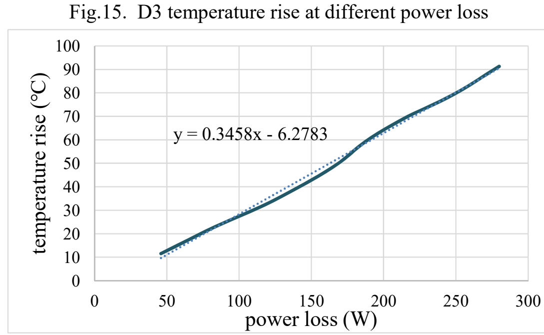

Fig.16. D5 temperature rise at different power loss

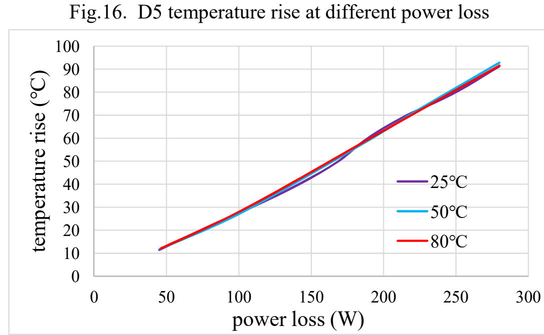

Fig.17. D5 temperature rise at different power loss and different coolant temperature

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