The Investigation of Humidity Absorption Behavior of Silicone Gel in HVIGBT Modules

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1. Introduction

Railway transportation is more energy-efficient than other transportation means and thus reduces the environmental impact of the entire transportation sector. Consequently, railway usage is being encouraged around the world to help combat global warming. In addition, to realize a low-carbon society, non-electrified railways are being electrified and more accumulator cars have been introduced. As a result, electric trains are now being used in various environments around the world.

Power modules for railway cars need to be small and efficient (low loss) and also more reliable than those for consumer goods and general industrial applications. Therefore, there is a growing need to evaluate resistance to diverse environments. In humid environments, in particular, it is difficult to completely eliminate the influence of humidity because modules have not been sealed. There are strong demands for higher humidity resistance and resistance evaluation technologies.

Under such circumstances, Mitsubishi Electric Corporation has worked to improve the humidity resistance of HVIGBT modules and establish humidity resistance evaluation technologies. Regarding penetration of moisture, HVIGBT modules are filled with silicone gel, which acts as a low-pass filter. Understanding the humidity absorption behavior of this silicone gel is important when assessing the humidity resistance of HVIGBT modules. However, the humidity absorption behavior at the level of the raw material (e.g., silicone gel) had not been studied. Therefore, we studied the humidity absorption behavior of silicone gel. This paper describes the results.

2. Humidity Absorption Behavior of Silicone Gel

Generally, IGBT modules are filled with silicone gel. Resin-like silicone gel absorbs moisture depending on the surrounding environment and it is known that the moisture content can be explained by the diffusion and dissolution of water vapor.[1][2] The water vapor solubility (c) is expressed by a diffusion coefficient (D) using Fick's law shown as formula (1). This diffusion coefficient (D) is expressed by a frequency factor (D_0), gas constant (R), activation energy (E_D), and temperature (T) as shown in formula (2).

$$\frac{\partial c}{\partial t} = \frac{\partial}{\partial x}\left(D\frac{\partial c}{\partial x}\right) \qquad (1)$$

$$D = D_0 \exp\left(-\frac{E_D}{RT}\right) \qquad (2)$$

Meanwhile, the solubility when the humidity absorption is sufficiently saturated ($c_{(t=\infty)}$) is expressed by a solubility coefficient (S) and vapor pressure (P_v) as shown in formula (3). This solubility coefficient (S) is expressed by a frequency factor (S_0), gas constant (R), and enthalpy (ΔH_S) as shown in formula (4).

$$c_{(t=\infty)} = S \cdot P_v \qquad (3)$$

$$S = S_0 \exp\left(-\frac{\Delta H_S}{RT}\right) \qquad (4)$$

It is important to determine the diffusion coefficient (*D*) and solubility coefficient (*S*) to understand the humidity absorption behavior of silicone gel. We therefore measured the trend of the increase in the weight of silicone gel when it absorbed moisture. As shown in Fig. 1, a metal cylinder with a radius of 2.5 mm was filled with silicone gel to a depth of 1.823 mm as a sample. Several such samples were prepared and dried at 50°C, 0%RH for eight hours. Then, one sample was put into a container at each of 25°C, 45%RH; 40°C, 45%RH; and 45°C, 45%RH and changes in the weight were measured.

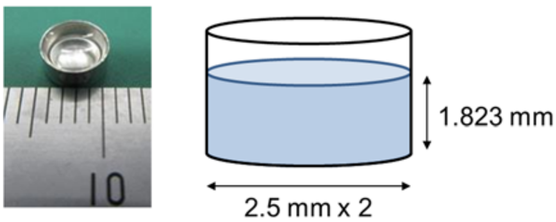

Fig. 1 Silicone gel sample for weight measurement under humidification

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Table 1 Vapor concentration at the end with various conditions

Ambient environment	Water vapor solubility of silicone gel	Vapor concentration of air
25 °C / 45%RH	2.89×10^{-4} mg/mm³	1.04×10^{-5} mg/mm³
40 °C / 45%RH	4.05×10^{-4} mg/mm³	2.30×10^{-5} mg/mm³
45 °C / 45%RH	4.39×10^{-4} mg/mm³	2.94×10^{-5} mg/mm³

Table 1 and Fig. 2 show the measurement results. As listed in Table 1, the water vapor solubility of silicone gel is approximately 20 times the vapor concentration of air. This suggests that water vapor had dissolved into the silicone gel. These results can be used to calculate the solubility (S) under each condition using formula (3). Figure 3 shows that the solubility coefficient (S) is negatively correlated with temperature. From Fig. 3 and formula (4), the calculated enthalpy (ΔH_S) is -26.8 kJ/mol and the frequency factor (S_0) is 4.12 x 10^{-12} mg/(mm^3·Pa).

Meanwhile, Bryan Ellis proposed a method to calculate the diffusion coefficient (D) approximately using the gradient of the increase in the solubility;[3] formula (5) is an approximate formula, where "L" is the thickness of the sample resin. In Fig. 4, the horizontal axis is $t^{0.5}/L$ and the vertical axis is $c(t)/c_{(t=\infty)}$. The gradient of the weight increase curve was calculated in the range of $0.2 < c(t)/c_{(t=\infty)} < 0.6$. Table 2 and Fig. 5 show the results.

$$\frac{c(t)}{c_{(t=\infty)}} = 2\sqrt{\frac{Dt}{L^2\pi}} \qquad (5)$$

Figure 5 shows that the water vapor diffusion coefficient of the silicone gel is positively correlated with temperature. From Fig. 5 and formula (2), the calculated activation energy (E_D) is 20.8 kJ/mol and the frequency factor (D_0) is 40.3 mm^2/s.

The solubility at 40℃, 80%RH calculated using the obtained solubility coefficient is 715 g/m^3. During rapid cooling, the solubility (SH) can be regarded as constant. Accordingly, from the curve of SH = 715 g/m^3 in Fig. 6, it is understood that when the temperature decreases by 10.5 K from 40℃, 80%RH, the inside of the silicone gel condenses. On the other hand, during rapid cooling, the absolute humidity (AH) of the air can be regarded as constant. From the curve of AH = 41 g/m^3 in Fig. 6, it is understood that when the temperature decreases by 4.4 K from 40℃, 80%RH, condensation occurs in the air. These results show that condensation tends to not occur in the silicone gel compared to in air.

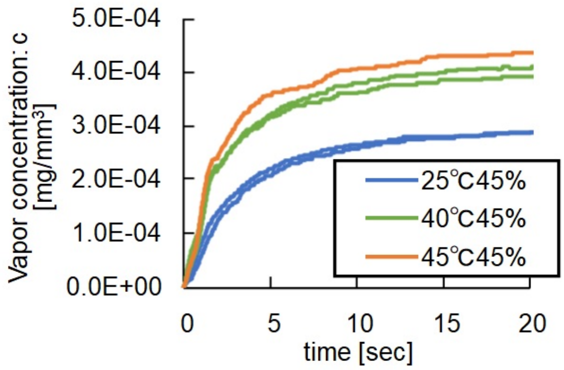

Fig. 2 Silicone gel weight increase trend with various conditions

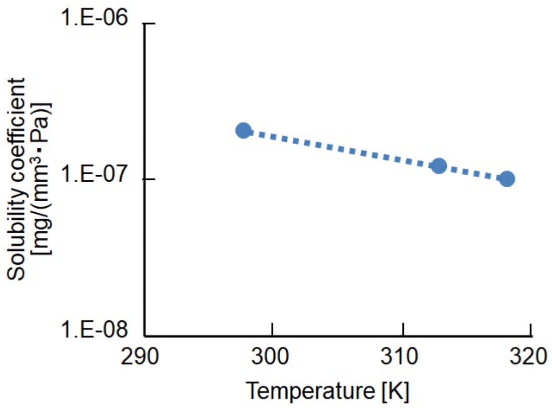

Fig. 3 Solubility coefficient temperature dependency of silicone gel

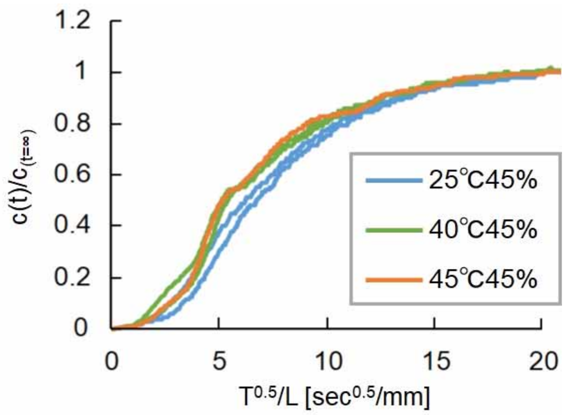

Fig. 4 Silicone gel weight increase trend with various conditions.

3. Humidity Absorption Behavior of Gel in Market Environments

The humidity absorption risk in market environments was studied using the calculated water vapor solubility coefficient and water vapor diffusion coefficient of the silicone gel. In this study, the thermal effect of devices' operation was not considered. The conditions were simplified and the temperature change due to the outside air were assumed to be the same as the temperature change of the devices. From data on environments in Tokyo and London in 2020, days on which the humidity was relatively high were selected from summer and winter and the humidity absorption by silicone gel was simulated. Figures 7 to 10 show the results.

The humidity near the chips (local humidity) tends to be higher in the early morning, which indicates that the condensation risk is the highest in the early morning. However, the results show that even when the relative humidity in the ambient environment is close to 100%, the humidity near the chips is below 100%. These simulation results also suggest that condensation tends to not occur inside modules compared to in the ambient environment.

Table 2 Diffusion coefficient of silicone gel

Ambient environment	Gradient of weight increase $2\times(D/\pi)^{0.5}$	Diffusion coefficient
25 °C/45%RH	0.108 mm/s$^{0.5}$	9.19×10^{-3} mm^2/s
40 °C/45%RH	0.135 mm/s$^{0.5}$	1.44×10^{-2} mm^2/s
45 °C/45%RH	0.137 mm/s$^{0.5}$	1.48×10^{-2} mm^2/s

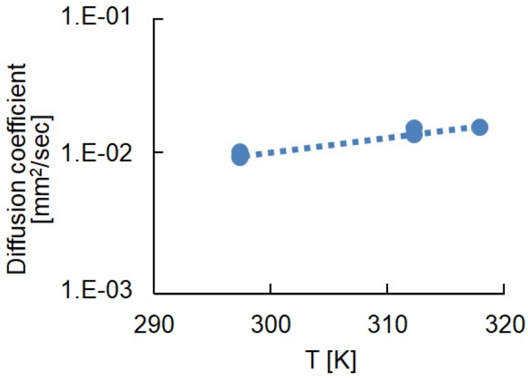

Fig. 5 Diffusion coefficient temperature dependency of silicone gel.

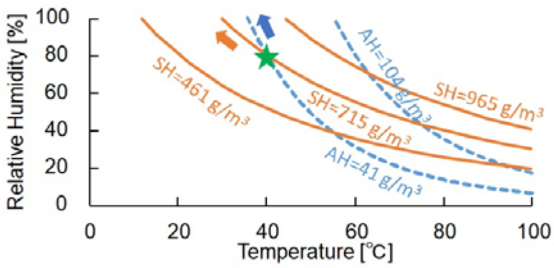

Fig. 6 Dissolved humidity (SH) & absolute humidity (AH)

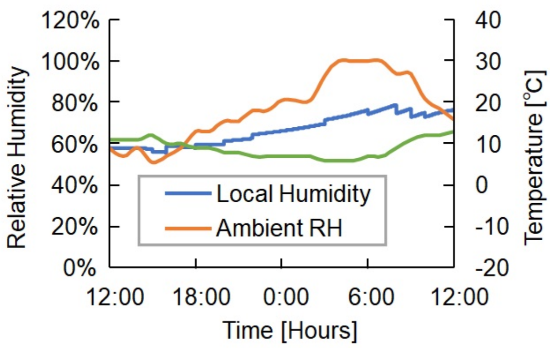

Fig. 7 Humidity absorption during day cycle in winter (1 – 2 Feb. 2020) in London.

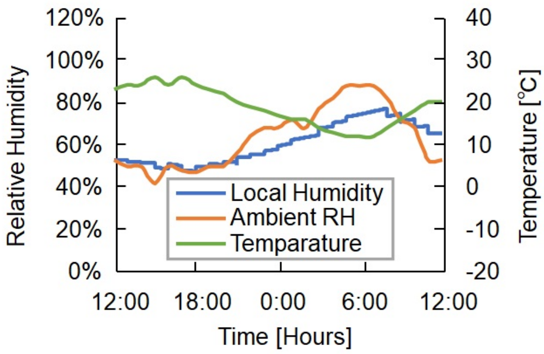

Fig. 8 Humidity absorption during day cycle in summer (1 – 2 Aug. 2020) in London.

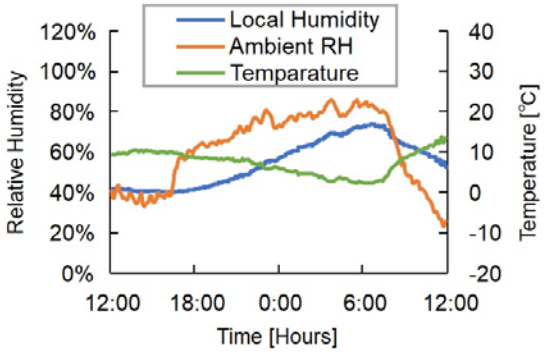

Fig. 9 Humidity absorption during day cycle in winter (4 – 5 Feb. 2020) in Tokyo.

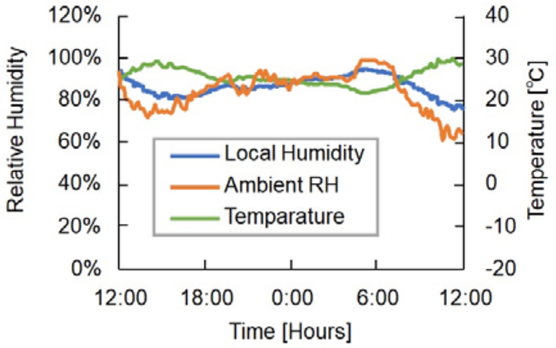

Fig. 10 Humidity absorption during day cycle in summer (31 Jul. – 1 Aug. 2020) in Tokyo.

4. Conclusion

Based on the experimental results, the water vapor solubility coefficient and water vapor diffusion coefficient of the silicone gel were calculated. The results showed that the condensation risk inside the silicone gel is smaller than in the ambient environment.

Mitsubishi Electric is using these developed humidity resistance evaluation and improvement technologies to increase the reliability of power semiconductor modules, contributing to realizing a low-carbon society and comfortable living.

References

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(3) B. Ellis, et al.: The effects of water absorption on a polyester/ chopped strand mat laminate, Composite, 14, 237 (1983)