ATTAINED TEMPERATURE DURING GAS FUELING AND DEFUELING CYCLES OF COMPRESSED HYDROGEN TANKS FOR FCV

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ABSTRACT

In this study, we conducted hydrogen gas filling and discharging cycling tests to examine the thermal behavior in hydrogen storage tanks under actual use conditions. As a result, it was confirmed that the gas temperature in the tank varied depending on the initial test conditions such as the ambient temperature of the tank and the filling gas temperature, and that the gas temperature tended to stabilize after several gas filling and discharging cycles.

INTRODUCTION

Currently, the gas cycle test that repeats filling a tank with hydrogen gas and releasing it is proposed as a method for evaluating compressed hydrogen tanks for FCV (hereafter, “tanks”), and 500 cycles of this test under various temperature conditions are planned. However, one cycle of the gas cycle test takes a long time; thus, the amount of time required for the evaluating the durability of tanks is a concern. In contrast, the conventional hydraulic pressure cycle test can be conducted easily and quickly. Since the replacement of the gas cycle test with the hydraulic pressure test is being considered, it is necessary to understand the temperature changes in the tank with the actual of gas cycle tests.

Thus far, we have investigated the behaviour of tank temperatures during hydrogen filling, and collected data that is useful for amending the current standards and for establishing the filling protocol to accomplish hydrogen filling safely and quickly at hydrogen stations. With conventional tests, we have obtained basic data of the behaviour of gas temperatures in a tank during hydrogen filling through filling tests on single tanks using pressure-rise pattern, filling rate, and filling gas temperature as parameters, and through rapid filling tests on fuel systems that are assumed to be mounted on actual vehicles.[1][2] However, to determine the safety of tanks in an actual environment, it is necessary to understand the temperature behaviour of tanks by assuming that hydrogen filling at hydrogen stations and running are performed continually.

In this study, we investigated the behaviour of the attained temperatures of gas in a tank with continuous repetition of cycles of filling and discharging, using gas cycle tests and assuming tanks in an environment of actual use, rather than performing only one cycle of filling and discharging of hydrogen. We report the results below.

1.0 TEST METHOD

1.1 Test Tanks

The tanks used in this test are described in Table 1. The test tanks were 70MPa compressed hydrogen tanks for FCV, a Type-3 tank (with aluminum liner) and a Type-4 (with plastic liner). Temperatures in the tank were measured by installing T-type sheath thermocouples. The representative temperature in the tank was defined as the temperature of the lower portion in the tank (T6), which was assumed to change most during gas discharging.[3] Furthermore, a pressure gauge to measure the gas pressure in the tank and a T-type sheath thermocouple to measure filling gas temperature were installed in the piping near the inlet of the tank.

Table 1. Test tanks.

Filling Pressure	70 [MPa]	
Type	VH3(Type-3)	VH4(Type-4)
Capacity	125 [L]	40 [L]
Size	D600-L1000[mm]	D300-L900[mm]

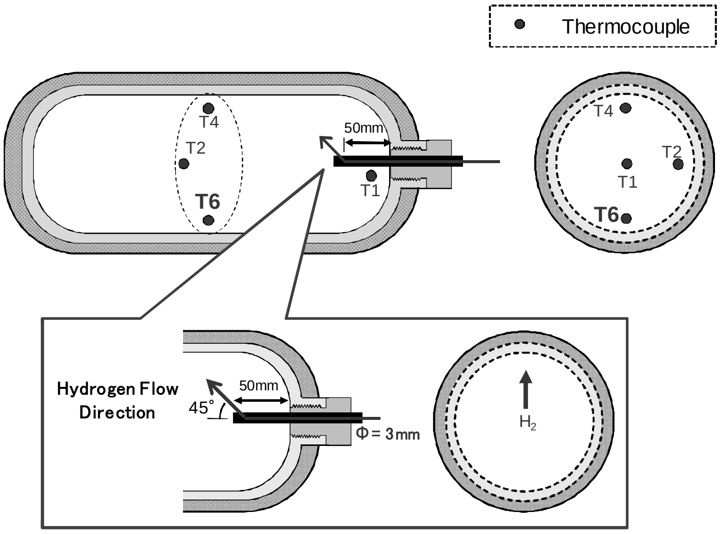


Figure 1. Measurement points of test tank

1.2 Test Equipment

The test equipment is depicted in Fig.2. For filling gas in test tanks, hydrogen gas stored in the gas storage bank unit, is controlled to a constant pressure rise rate by the pressure sensor and the flow meter. The gas temperature is adjusted by the precooling unit. When the gas is discharged from the tank, the gas is discharged at a constant flow rate by the flow control valve, and recovered to the buffer tank with the pressure increased by the compressor, and then it was stored again in the gas storage bank unit. The test tanks are installed in a thermostatic chamber (blast-resistant chamber) to control the temperatures of the tank itself, the gas in the tank, and the environmental temperatures of the tank.

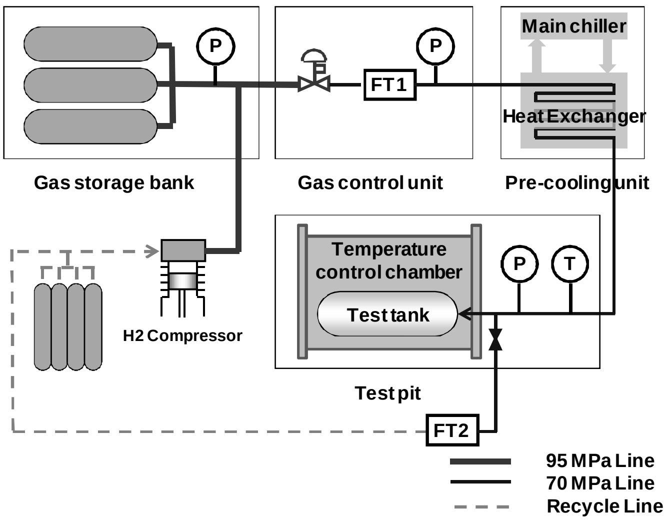


Figure 2. Flow diagram of filling test equipment

1.3 Test Conditions

The test conditions is listed in Table 2. For the temperature of gas for filling the tank and the environmental temperature of the tank, a total of six conditions are set by assuming an conditions of actual use.

Tests were conducted in two ways: starting with filling (hereafter, “start with filling”) and starting with discharging (hereafter, “start with discharging”). The discharging was continued for 1 or 2 hours while the pressure decrease rate in the tank was kept constant. For filling, the same pressure rise rate was set for both the Type-3 and the Type-4 tanks, and tanks were filled at a filling rate that did not allow the temperature to exceed 85^{o}C as the maximum operating temperature of the Type-4 tank, or 16MPa/min as the maximum filling pressure.

Table 2. Test Conditions

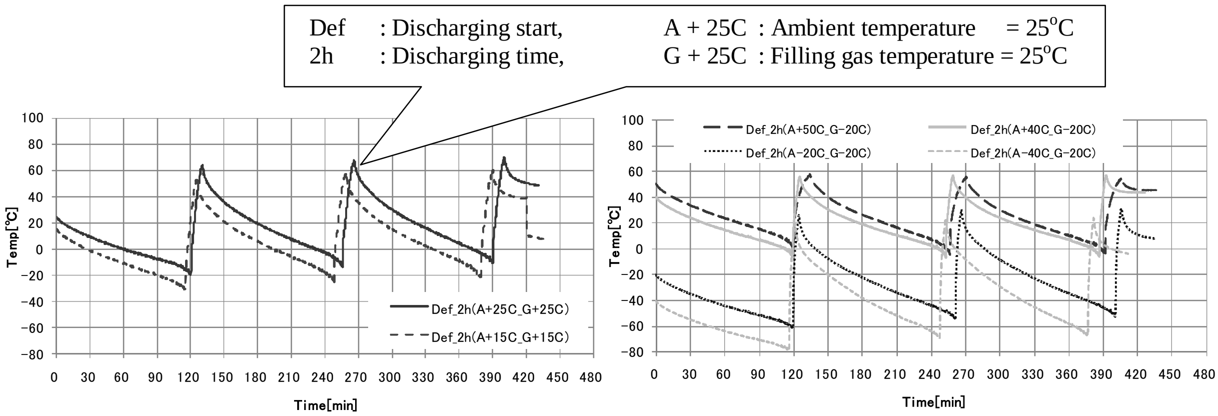
	i	ii	iii	iv	v	vi
Ambient Temp.[^{o}C]	15	25	40	50	-20	-40
Filling Gas Temp.[^{o}C]	15	25	-20	-20	-20	-20
Pressure Range	1 ～ 70[MPa]					
Starting Condition	Filling Start Discharging Start					
Pressure Rise Rate of Filling Gas	5 ～ 16 [MPa/min] （Constant Rate to 70MPa）					
Flow Rate of Discharging Gas	Constant Flow Rate					
Discharging Time	1 or 2 [hour]					

2.0 RESULTS AND DISCUSSION

2.1 Influence of Environmental Temperature and Gas Filling Temperature

From the test results for the Type-3 tank, Fig.3 presents an example of the behaviour of gas temperatures in the tank at each temperature condition for a start with discharging. Fig. 4 indicates the gas temperature in the tank immediately after each cycle of filling and discharging. When the cycles were repeated, changes in the attained temperature on the high-temperature side and low-temperature side tended to stabilize after the second cycle. Furthermore, the attained temperature changed according to the environmental temperature and filling gas temperature as parameters. Specifically, it shifted higher as the environmental temperature became higher, while the filling gas temperature was kept constant.

From the test results for the Type-4 tank, Fig.5 indicates the behaviour of temperatures under the same test conditions as for the Type-3 tank. The behaviour of gas temperatures in the Type-4 tank also tended to stabilize after the second cycle. However, it was a maximum of 20^{o}C higher than the attained temperature in the Type-3 tank under the same temperature, and a maximum of 20^{o}C lower on the low-temperature side. It can be assumed that this result occurred because the thermal conductivity of the liner material of the Type-4 tank (plastics: 0.4[W/(m･K)]) is less than that of the liner material of the Type-3 tank (aluminum alloy: 180[W/(m･K)]), and the heat transfer between the gas inside the tank and the tank itself is less.



(a) 15 °C and 25 °C Filling Gas (b) −20 °C Filling Gas (precool)

Figure 3. Thermal behavior of Type-3 tanks in gas filling and discharging cycles

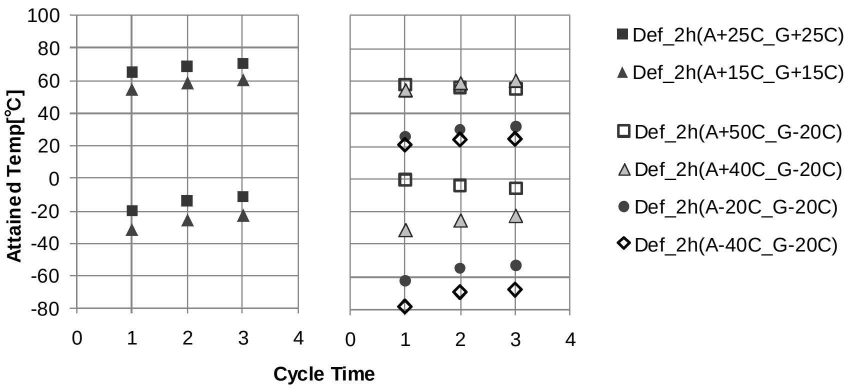
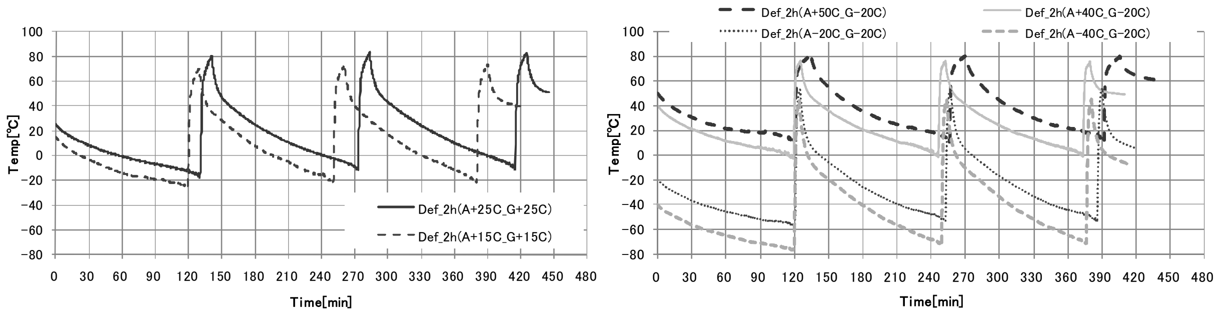


Figure 4. Thermal behaviour of Type-3 tanks after each cycle of gas filling and discharging



(a) 15 °C and 25 °C Filling Gas (b) −20 °C Filling Gas (precool)

Figure 5. Thermal behaviour of Type-4 tanks in gas filling and discharging cycles

2.2 Influence of Change in Discharging Time

From the test results for the Type-3 tank, Fig.6 presents an example of the temperature behaviour of the gas inside the tank for start with discharging, and discharging times of 1 or 2 hours. In each cycle, the attained temperature after the second cycle became stable when the discharging time was reduced from 2 hours to 1 hour under the same temperature, and the attained temperature of the gas in the tank on the low-temperature side decreased further. Tests on the Type-4 tank under the same condition exhibited the same trend as in the Type-3 tank (described above). It is assumed that this result

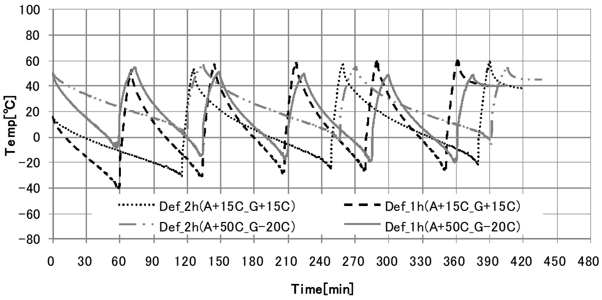


Figure 6. Thermal behaviour of Type-3 tanks in the case of different discharging time

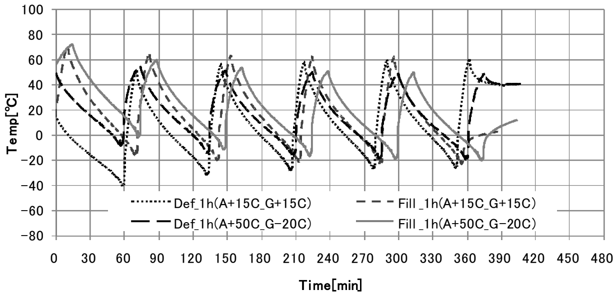


Figure 7. Thermal behaviour of Type-3 tanks in the case of different starting conditions

occurred because the amount of heat transfer between the gas in the tank and the tank itself during discharging was proportional to the length of discharging time; the input heat to the gas decreased as the discharging time decreased, and thus the gas temperature in the tank decreased further.

2.3 Influence of Change in Test Starting Conditions

From the test results for the Type-3 tank, Fig.7 presents an example of the temperature behaviour of the gas in the tank under the test condition of starting with discharging or starting with filling. The temperature condition was the same, although the initial attained temperatures were different. Results indicated that the temperatures became stable after several cycles. Furthermore, the test results for the Type-4 tank indicated the same trend of becoming stable as the Type-3 tank. It can be assumed that this result occurred because the heat transfer between the tank and filling gas and the gas in the tank reached a balance. Therefore, it is assumed that the test starting condition has little influence on the attained temperature of the gas in the tank.

3.0 DERIVING EMPIRICAL FORMULAE OF ATTAINED TEMPERATURE

The results of this test indicated that the final attained temperature after several cycles became stable on both the high-temperature and the low-temperature sides in both the Type-3 and the Type-4 tanks. Furthermore, the behaviour of the attained temperature under each test condition had almost the same differences from the environmental temperature and was proportional to each test parameter (e.g., filling gas temperature, precooling temperature, and discharging rate). From these relationships, we obtained the linear expression of the attained temperature with respect to each test parameter and obtained the following empirical formulae for each tank.

・Empirical formula for the attained temperature of the Type-3 test tank

$$T_H ;\, c = 0.67\, V_F - 5.40\, V_D + 0.55\, (T_G - T_A) + T_A + 45.03 \quad (1)$$

$$T_L ;\, c = 0.50\, V_F - 15.86\, V_D + 0.23\, (T_G - T_A) + T_A - 30.95 \quad (2)$$

・Empirical formula for the attained temperature of the Type-4 test tank

$$T_H ;\, c = 1.83\, V_F - 2.82\, V_D + 0.43\, (T_G - T_A) + T_A + 47.48 \quad (3)$$

$$T_L ;\, c = 0.22\, V_F - 17.87\, V_D + 0.07\, (T_G - T_A) + T_A - 26.70 \quad (4)$$

where, T_H; c : Attained temperature on the high-temperature side [°C]
T_L; c : Attained temperature on the low-temperature side [°C]
V_F : Gas filling rate [MPa/min] (5 to 16)
V_D : Gas discharging rate [MPa/min] (0.58 to 1.17)
T_G : Filling gas temperature [°C] (-20 to 25)
T_A : Environmental temperature [°C] (-40 to 50)

The applicable range of the above parameters is the range of test conditions implemented in this test. These conditions are similar to those in actual practice, considering the filling rate from the dispenser and the hydrogen consumption (discharging) rate of hydrogen-fuelled vehicles. A list of measured values (T_H;r, T_L;r) and estimated values from empirical formulae (T_H;c, T_L;c) of attained temperature are presented in Fig.8. The maximum relative error between the estimated value from the empirical formula and the measured value was 7^{o}C.

It is assumed that the values of the coefficients of this empirical formula may vary when the value of any parameter is beyond the applicable range or when the ratios of composite materials, form of the tank, or capacity differ, even if the type of tank is the same. Therefore, to obtain a more accurate estimated value, it is necessary to compare the measured values from the gas cycle tests under various conditions with the estimated values from empirical formulae, and then examine the results.

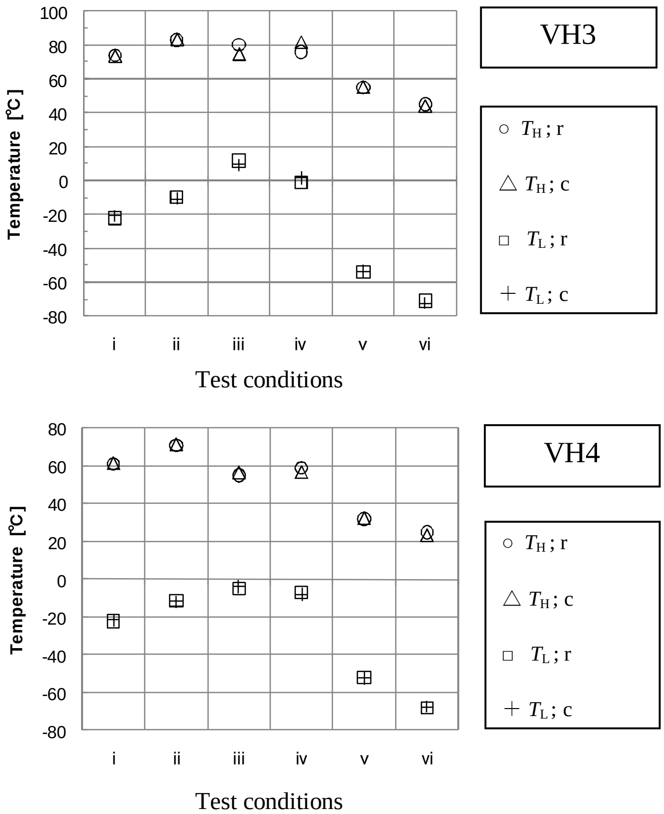


Figure 8. Attained temperature of each condition after several cycles of gas filling and discharging

4.0 SUMMARY

Rather than focusing on only one cycle of filling and releasing hydrogen gas, we conducted gas cycle tests to investigate the behaviour of the attained temperature of the gas in the tank when cycles of filling and releasing hydrogen gas were repeated. We obtained the following results.

- Although the attained temperature changed with changes in parameters (e.g., environmental temperature, filling gas temperature, discharging time, and test starting condition in both the Type-3 tank (with aluminum liner) and the Type-4 tanks (with plastic liner), its became stable after several cycles.
- Under the same temperature, the attained temperature in the Type-4 tank was higher than that in the Type-3 tank. This phenomenon can be considered to be caused by the difference in heat transfer due to the difference in liner material and tank capacity.

- For the attained temperatures during gas filling and discharging, the estimated value of the attained temperature calculated using an empirical formula roughly agreed with the measured value; therefore, this method is useful for estimating the attained temperature.

We investigated the gas temperature in the tank during continuous cycles of gas filling and discharging, assuming an environment of actual use, although the attained temperature differed with test conditions. We found that the attained temperature became stable after the second cycle; this finding is important for considering the safety of tanks.

For further understanding of gas temperatures in a tank, it is important to accumulate more data by conducting tests on many tanks under other temperature conditions in the future. In this study, we analyzed the data obtained and considered that surface temperature, volume, and heat transfer differ depending on the type of tank. In doing so, we confirmed the possibility of understanding the behavior of gas temperature in a tank by assuming an environment of actual use in more detail and by improving the accuracy of common formulae that enable estimating the attained temperature from test parameters. We examined the replacement of the gas cycle test with the hydraulic pressure cycle test to evaluate tank performance. The results indicate that this test method is useful for understanding tank performance.

5.0 ACKNOWLEDGMENTS

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