HYDROGEN FAST FILLING TO A TYPE IV TANK DEVELOPED FOR MOTORCYCLES

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ABSTRACT

Hydrogen is one of possible alternative energy sources to replace fossil fuels in transportation sector. Hydrogen fuel cell vehicles (FCVs) are expected to play an important role in the future. A tank to store compressed hydrogen is necessary for the FCVs due to the long-distance driving as well as that of conventional vehicles. It is also necessary that refueling the tank should be completed within a few minutes because of user convenience. In this study, a fast filling of high pressurized hydrogen is concerned for a Type IV tank which has been developed for motorcycles. Due to restrict the temperature rise up to 85 degrees Celsius for fuel cell system integrity, different scenarios of fast filling up to 70 MPa are investigated. A pressure ramp rate is kept at a constant value with or without intermissions. All cases applied in this study indicate that the gas temperature in the tank does not always exceed 85 degrees Celsius until the end of filling. The temporal decrease of inside gas temperature is appeared after the rapid rise in the early 10 seconds of filling. It is estimated that the heat produced by compression of hydrogen transfers to the inside wall immediately, since the inner surface area to tank volume ratio becomes large as the tank size is small. Therefore the decrease of gas temperature obtained in this study is a characteristic phenomenon in small size tanks.

1.0 INTRODUCTION

Recent environmental and energy safety issues promote the change of energy source from the fossil fuel to others. Hydrogen that is a clean fuel and an energy carrier represents a possible alternative energy source. Hydrogen can be used for a broad range of applications, as for the transportation sector the hydrogen energy is also considered as an alternative energy source. Recently hydrogen fuel cell vehicles (FCVs) which are expected to play an important role in the future have been researched significantly.

The FCVs have a fuel cell stack instead of an internal combustion engine used for conventional vehicles. The fuel cell stack converts hydrogen gas with oxygen from the air into electricity directly to drive the wheels. The direct electrode reaction of hydrogen and oxygen provides higher energy conversion efficiency compared with combustion engines affected by Carnot cycle restriction. However, it is well known that the hydrogen energy density at atmospheric pressure is very low compared with fossil fuels used for conventional vehicles therefore a compressed hydrogen tank is considered in general use of FCVs. To store much hydrogen energy on the FCVs, an extremely high compression of hydrogen is required.

Tank to store high pressure hydrogen can be categorized into four types [1]. Types I and II are a traditional steel storage which mainly employs the compressed natural gas vehicles. On the other hand Types III and IV, which are carbon fiber full-wrapped cylinders, are mainly developed and researched for FCVs since these allowable maximum pressure is higher than that of Types I and II. The hydrogen gas stored in the Types III and IV can be compressed up to 70 MPa achieving the long-distance driving as well as that of conventional vehicles.

While the hydrogen is refuelled to the tank, pressure in the tank rises to 70 MPa from several MPa. Since the refuelling should be completed within a few minutes because of user convenience, a fast filling of high pressurized hydrogen is concerned at hydrogen stations. However, high pressure ramp rate induces a rapid increase of gas temperature inside the tank. Such a high temperature due to the rapid compression of hydrogen gas compromises the structural integrity of the hydrogen storage system. For this reason, allowable maximum gas temperature inside the tank is set to 85 degrees Celsius [2,3].

Type III and IV tanks have respectively a metal liner and a plastic liner. Although the Type IV tank, which is used in this study, has an advantage of light weight, higher temperature rise due to the rapid compression of hydrogen gas during fast filling process is a disadvantage. Thermal property of plastic liner causes higher temperature rise in the tank. The mechanism of temperature rise during filling process for Type III and IV tanks has been significantly researched analytically and experimentally over the last decade.

Dicken and Mérida [4] measured gas temperature at 63 points inside a 74 liters Type III tank during the hydrogen filling. Effects of the initial mass and fill rate on the temperature rise during filling were investigated. It is revealed that slower fillings produce a temperature field with a significant stratification in the vertical direction caused by buoyancy forces. Their experimental results are often used to validate computational fluid dynamics (CFD) models. Heitsch et al. [5], Suryan et al. [6], and Wang et al. [7] referred to these experimental results. Heitsch et al. validated a 3-dimensional model using the commercial CFD software CFX 11. Suryan et al. investigated the suitable turbulence model for the hydrogen fast filling process. Four turbulent models based on Reynolds Averaged Navier-Stokes equation were compared. Wang et al. validated a 2-dimensional axisymmetric model using the commercial CFD software Fluent 13.0. These CFD approaches supplied detailed information on flow and temperature distribution inside the tanks during hydrogen fast filling.

The CFD technique is also applied to other configurations and conditions. Galassi et al. [8] investigated the effect of different pressure patterns using CFX 12.1. A 3-dimensional model of a 70 MPa type IV tank is assumed. Li et al. [9] studied the effects of tank geometry and inconstant mass flow rate on temperatures rise and distribution inside the tank during hydrogen fast filling. Cylinders of different length to diameter ratios and different inlet diameters were simulated by a 2-dimensional axisymmetric swirl CFD model built in Fluent 13.0.

Monde et al. [10] developed a simple thermodynamic model for filling of hydrogen tank. It was assumed that the gas temperature inside the tank is uniform, i.e. fluid dynamics inside the tank does not considered. The temperature rise during filling process is well predicted by the simple model considering heat flux through the tank wall estimated with a reasonable heat transfer coefficient.

Kim et al. [11] investigated thermal flow characteristics during hydrogen filling process of a Type IV tank with an internal volume of 72 liters. The experimental results for 5 different initial pressures of the tank were compared with results obtained by a transient 3-dimensional numerical simulation considering conjugate heat transfer between hydrogen gas and tank wall. The change of hydrogen gas pressure in the tank was in good agreement, while the maximum temperature of the hydrogen gas inside the tank was over-predicted by the numerical simulation.

Liu et al. [12] investigated experimentally the thermal behaviours such as gas temperature rise and distributions inside 35 MPa, 150 liters Type III tank during fast filling. While Zhao et al. [13] simulated the above experiment with a 2-dimensional axisymmetric simulation based on compressible fluid dynamics. Thermal condition of the tank during fast filling was revealed in detail. Zheng et al. [14] researched 70 MPa, 74 liters Type III tank experimentally and numerically.

Most studies on the hydrogen filling process suppose that the tank is used for automobile, namely relatively large tank is concerned. On the other hand, the volume of a compressed hydrogen tank for fuel cell motorcycles is assumed to be less than about 20 liters. There are not many researches on such a small tank. To realize the fuel cell motorcycle, many problems concerning its relatively small size must be solved. Such a small tank may have different thermal characteristics during hydrogen fast filling compared with those of a large automobile tank. In this study, we experimentally investigate thermal characteristics of such a small tank during hydrogen fast filling.

2.0 EXPERIMENT

A Type IV tank with 11 liters is used to investigate thermal conditions when high-pressurized hydrogen is filled to the tank. Outer diameter of the cylindrical tank is 230mm and the axial length 550mm. Initial pressure of the tank is set at about 1.0 MPa and initial gas temperature 40°C. The tank is set inside an explosion containment chamber which inside temperature is controlled to keep 40°C during hydrogen fast filling. It is a sever condition for the tank that the environmental temperature and initial tank temperature are 40°C.

Figure 1 shows the position of T type thermocouples of 0.5mm in diameter to measure temperature change during filling process. The thermocouples are inserted on the side opposite from the inlet nozzle. The temperatures on the inside and outside walls as well as the inside gas temperature are measured at upper, middle, and bottom points, denoted as points 1, 2, and 3. The thermocouples for measuring the inside gas temperatures are set 10mm away from the internal wall surface. Hydrogen gas cooled to about −40°C to minimize the increase in gas temperature is supplied through a tube 3mm in diameter set on the opposite side of the thermocouples. The inlet nozzle is tilted 45° upward to ensure uniform temperature distribution [14].

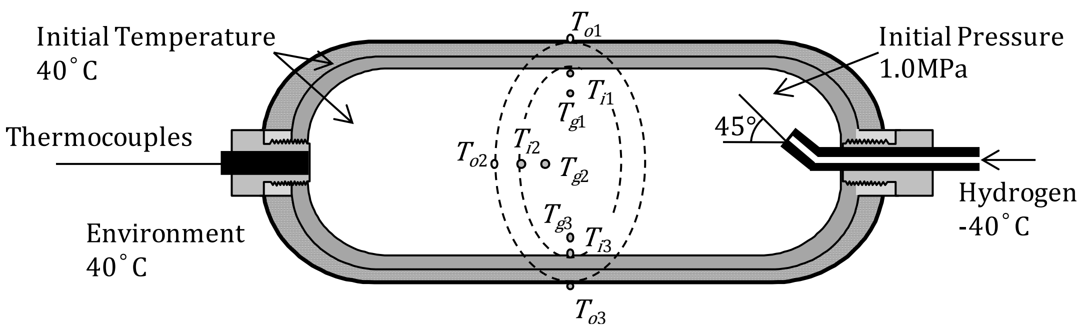

Figure 1 Position of thermocouples

3.0 RESULTS AND DISCUSSION

3.1 Effect of Pressure Ramp Rate

When the hydrogen is refueled, a rate of pressure rise is kept at a constant value, 1.0 or 0.5 MPa/s. The tank pressure is controlled well until the internal pressure reaches 70 MPa of the target pressure as shown in Figure 2. Filling time is about 69 seconds for the case of 1.0 MPa/s, and about 138 seconds for the case of 0.5 MPa/s. The inside gas temperature changes rapidly in the early 10 seconds shown in Figures 3, 4, and 5. The gas temperature reaches about 74°C which is maximum value during the hydrogen filling process. After the rapid rise, temperature decreases to about 65°C and increases again gradually. At the end of filling, the inside gas temperature reaches about 70°C. The temporal decrease of inside gas temperature after the rapid rise which is not appeared clearly in fast fillings of large size tank is a characteristic phenomenon in small size tanks. It is estimated that the absorbed heat to the tank wall is larger than produced heat inside the tank after the rapid rise. Since the inner surface area to tank volume ratio becomes large as the tank size is small, the heat produced by compression of hydrogen transfers to the inside wall immediately. Significant difference in the maximum temperature is not appeared in two cases due to the fast heat transfer. Since the tank has a margin of 10°C to the allowable maximum temperature, it is possible that the pressure ramp rate is set faster than 1.0 MPa/s to reduce the filling time safely for user convenience.

The inside wall temperatures shown in Figures 6, 7, and 8 are similar to the results of inside gas temperatures. However, the inside wall temperatures at upper point are higher than other points in the early filling process. Since the inlet nozzle is tilted 45° upward, it is estimated that the hydrogen gas flow effectively through the upper wall surface, and that the heat transfer rate on the upper wall becomes higher. As a result, the gas temperature T_{g1} is lower than T_{g2} and T_{g3} as shown in Figures 3 and 4.

Figure 9 indicates that the average outside wall temperature is almost kept at constant until the end of filling. However, it is found that the wall temperature in the case of 0.5 MPa/s starts to increase slightly after 100 seconds. It is estimated that the heat produced by compression of hydrogen gas reaches to the outside surface of the tank wall at about 100 seconds. Therefore, when the fast filling is finished by 100 seconds thermal conditions of the tank during hydrogen filling does not depend on the surrounding condition of the tank.

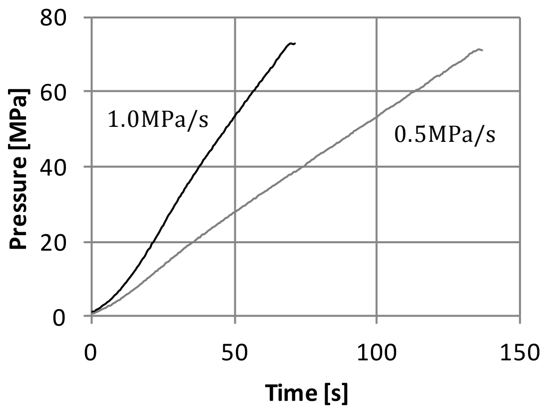

Figure 2 Tank pressure during hydrogen fast filling (Initial pressure:1.0 MPa)

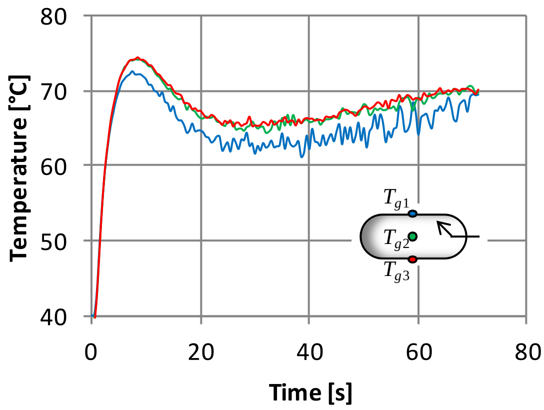

Figure 3 Inside gas temperature under the pressure ramp rate 1.0 MPa/s

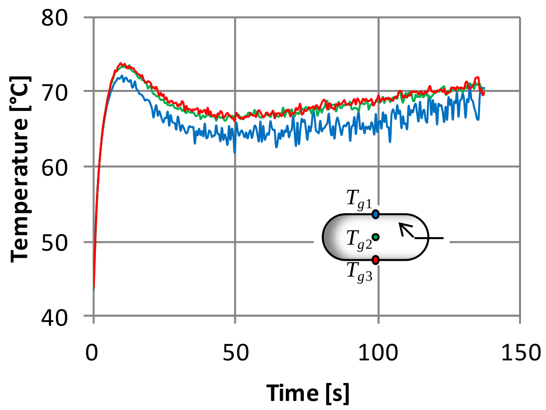

Figure 4 Inside gas temperature under the pressure ramp rate 0.5 MPa/s

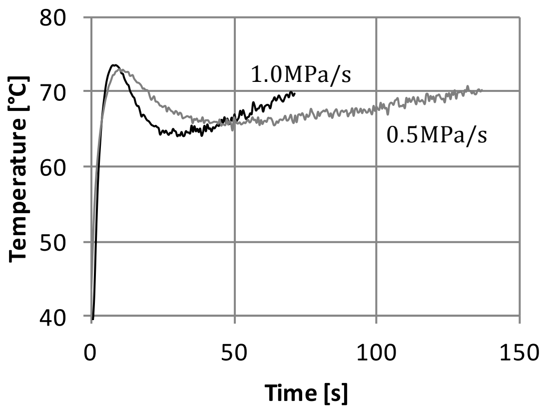

Figure 5 Average gas temperature in the tank during hydrogen fast filling

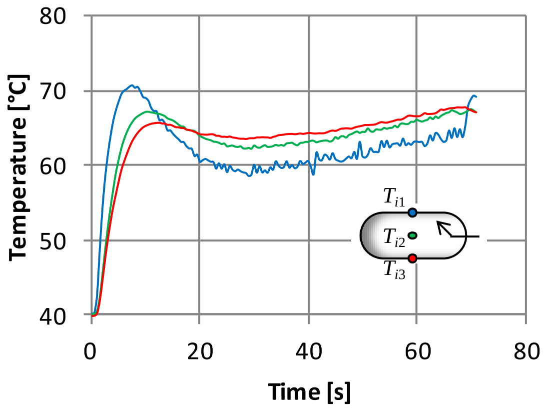

Figure 6 Inside wall temperature under the pressure ramp rate 1.0 MPa/s

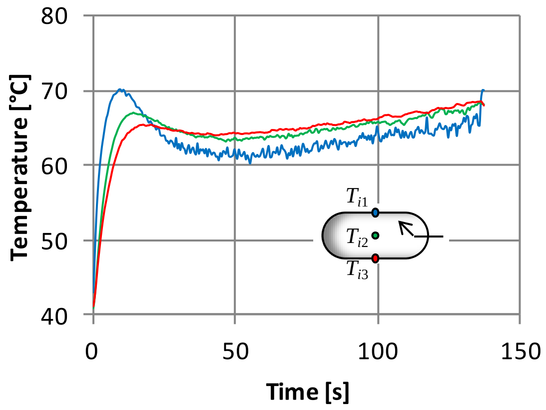

Figure 7 Inside wall temperature under the pressure ramp rate 0.5 MPa/s

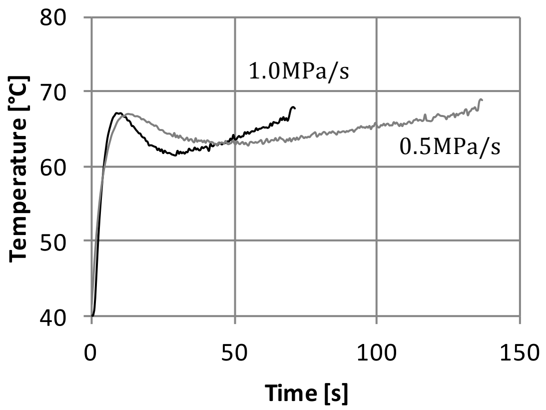

Figure 8 Average inside wall temperature

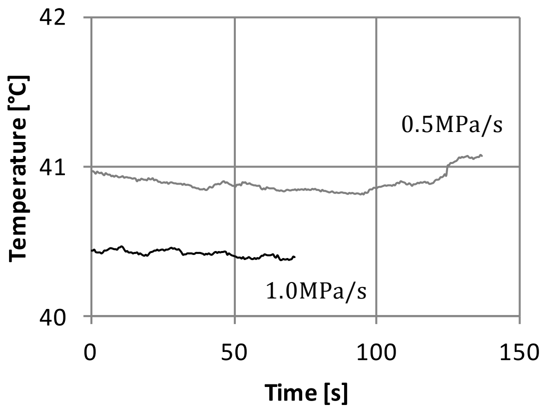

Figure 9 Average outside wall temperature

3.2 Effect of Intermissions during Filling Process

Hydrogen filling process with intermission is considered to control the temperature rise due to the fast filling of hydrogen. To complete the filling within 3 minutes for user convenience, 2 filling processes listed in Table 1 are designed. Figure 10 shows the filling process listed in Table 1. The filling process of 2 steps includes one intermission. After the hydrogen filling is performed with 1.0 MPa/s until 29 seconds, the hydrogen filling stops until 140 seconds. Then, hydrogen filling with 1.0 MPa/s is started again and it is kept until 180 seconds. The filling process of 4 steps includes 3 intermissions. The hydrogen filling stops 37 seconds at 19, 76, and 133 seconds. It is found that the pressure ramp rates are controlled well in the experiment as shown in Figure 11 compared with Figure 10.

Table 1 Filling process with intermissions

2 steps	Time [s]	0	29	140	180				
	Pressure [MPa]	1	30	30	70				
4 steps	Time [s]	0	19	56	76	113	133	170	180
	Pressure [MPa]	1	20	20	40	40	60	60	70

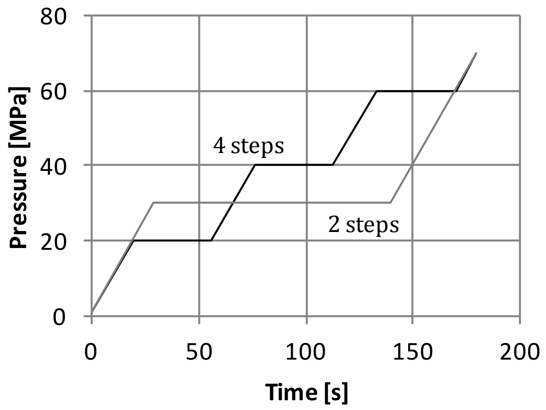

Figure 10 Tank pressure of filling process listed in Table 1

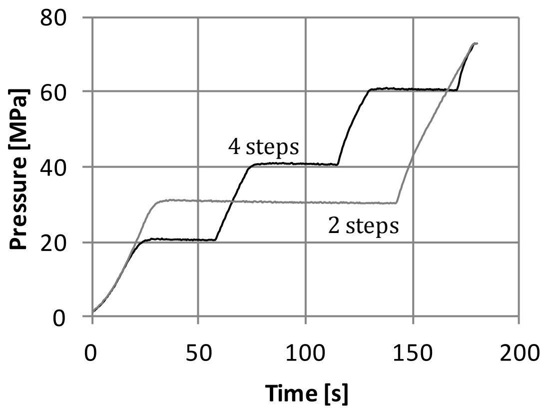

Figure 11 Tank pressure obtained by experiments during hydrogen fast filling with intermissions

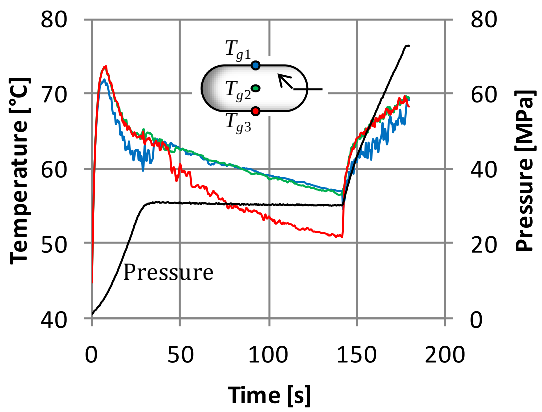

Figure 12 Inside gas temperature and tank pressure (2 steps)

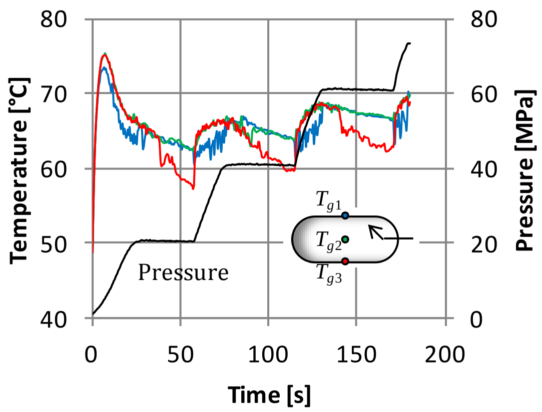

Figure 13 Inside gas temperature and tank pressure (4 steps)

The inside gas temperature changes rapidly in the early 10 seconds shown in Figures 12 and 13. After the gas temperature reaches about 74°C, the gas temperature decreases to 65°C at 30 seconds. This phenomenon is similar to the result of Figure 3. The intermission after the early 10 seconds is not effective clearly to decrease the maximum gas temperature in the tank. The intermissions should be carried out in the early 10 seconds at least. Even if there is a difference of 10 MPa between the tank pressure in the cases of 2 steps and 4 steps at 30 seconds, the effects of the tank pressure on the gas temperature are not clear.

The inside gas temperature at the bottom points, T_{g3}, is decreases lower than other measurement points after about 40 seconds. It is indicated that the temperature stratification in the vertical direction is produced in the tank due to buoyancy forces. Similar temperature profile in a Type IV tank with 74 liters is reported by Dicken and Mérida [4].

After the second filling starts at 56 seconds in the case of 4 steps, the inside gas temperature rises until the end of the second filling. The gas temperature at the upper measurement point, T_{g1}, is lower than the others during the hydrogen filling. While the gas temperature at the bottom measurement point, T_{g3}, becomes lower than the others during the stop of filling. Namely the gas temperature distribution having lower temperature in the upper region produced by the injected gas is changed immediately to the distribution where the lower temperature region is in the bottom region at the stop of filling. At the other intermissions, similar phenomenon is appeared.

The inside wall temperature also rises rapidly in the early 10 seconds shown in Figures 14 and 15. However, the temperature at upper point is higher than other points in the early process since the inlet nozzle tilted 45° upward makes the heat transfer rate on the upper wall higher.

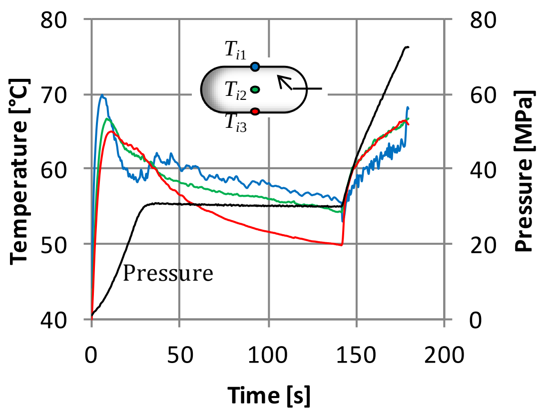

Figure 14 Inside wall temperature and tank pressure (2 steps)

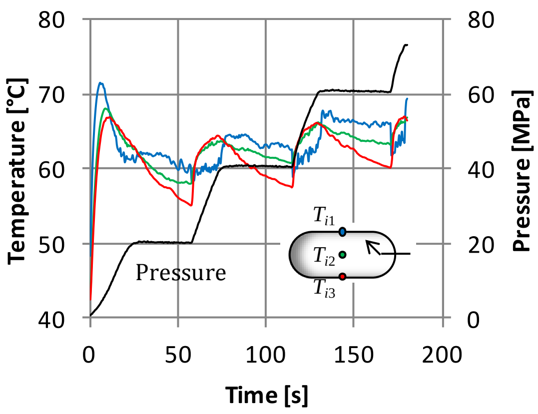

Figure 15 Inside wall temperature and tank pressure (4 steps)

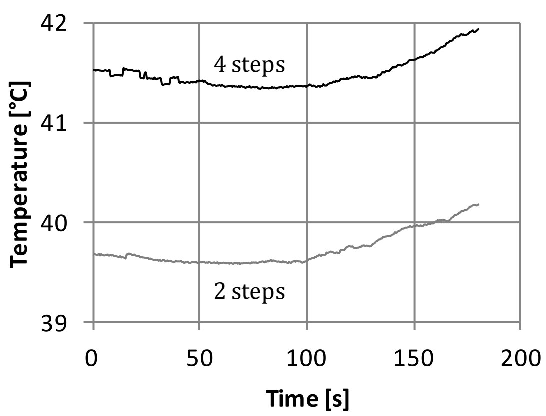

Figure 16 Average outside wall temperature

Figure 16 shows the average outside wall temperature. The surround gas temperature is almost kept at constant until the end of filling, while the outside wall temperatures increase gradually after 100 seconds. Since the similar phenomenon is also observed in Figure 9, about 100 seconds is necessary to reach the heat produced by compression of hydrogen gas to the outside wall of the Type IV tank.

4.0 CONCLUSIONS

To investigate the thermal characteristics of the Type IV tank developed for motorcycles, different scenarios of hydrogen fast filling up to 70 MPa were carried out to compare each other. All cases applied in this study indicate that the gas temperature in the tank does not always exceed the allowable maximum temperature 85°C until the end of filling.

The inside gas temperature changed rapidly in the early 10 seconds, and reached about 74°C which is maximum value when the pressure ramp rate was kept at a constant value, 1.0 or 0.5 MPa/s. The temporal decrease of inside gas temperature is appeared after the rapid rise. It is estimated that the heat produced by compression of hydrogen transfers to the inside wall immediately, since the inner surface area to tank volume ratio becomes large as the tank size is small. Therefore the decrease of gas temperature obtained in this study is a characteristic phenomenon in small size tanks.

The inside wall temperature at upper point was higher than other points in the early filling process because the inlet nozzle is tilted 45° upward in this experiment. It is estimated that the heat transfer rate on the upper wall became higher. As a result, the gas temperature at upper point was lower than other points.

About 100 seconds is necessary to reach the heat produced by compression of hydrogen gas to the outside surface of the tank. Therefore the surrounding condition of the tank is not important to estimate the inside gas temperature change for the fast filling finished by 100 seconds.

To control the temperature rise due to the fast filling of hydrogen, the effect of intermissions during filling process were investigated. As a result, the intermissions were not effective clearly to decrease the maximum gas temperature in the tank. The intermissions should be carried out in the early 10 seconds at least. The inside gas temperature at the bottom points decreased lower than other measurement points after the stop of filling. It is indicated that the temperature stratification in the vertical direction was produced in the tank immediately due to buoyancy forces.

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