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Characteristics of CFRP hydrogen storage vessel on rising temperature in the filling process

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Abstract

Different types of materials are commonly used for constructing hydrogen pressure vessels. However, carbon fiber reinforced plastic (CFRP) materials are commercially used in hydrogen vessels now a day. Commercially used aluminium liner vessel is easy to construct and posses high thermal conductivity compared to other commercially available vessels. However, compared to CFRP liner vessel, it has low strength capacity and safety factors. Therefore, now a day, CFRP liner vessels are becoming more popular in modern hydrogen vehicle systems. Moreover, CFRP vessel has light weight advantage. CFRP, although, has many desirable properties in reducing the weight and in increasing the strength, it is also necessary to keep the material temperature below 85°C for maintaining stringent safety requirements. Because while filling process occurs, the temperature can be exceeded due to the compression works of the gas flow. Therefore, it is very important to optimize the hydrogen filling system for avoiding temperature rise to cross the critical limit of damaging CFRP wall vessel.

Computer simulation has been conducted to characterize the CFRP storage vessel in hydrogen filling to optimize the technique. Three hydrogen vessels with different volumes and with different filling pressure have been used to characterize the temperature rise of the wall materials in filling system. The wall materials have been considered as aluminum liner material and CFRP composite materials. Supply tanks have been played important roles in supplying hydrogen in different storage tanks with different supply pressures. Gas temperatures have been measured inside representative vessels in the supply reservoirs and at the inlet to the test tank during filling. In simulation, the geometry has been simplified to a cylinder for illustration purposes. The rise in temperature of the hydrogen and the tank wall during the filling of hydrogen into the actual tank with CFRP liner has been simulated with different filling conditions at Saga University and the results have been compared with JARI (Japan Automobile Research Institute) experimental data as well.

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Keywords: CFRP hydrogen vessel; hydrogen filling system; thermal properties; vessel safety.

Nomenclature

A	vessel internal surface area (m^2)
l	total thickness of the wall (m)
P	pressure (MPa)
Q	heat loss into wall, (kJ)
T	temperature (°C or K)
t	time (sec)
x	argument in the x-direction

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Greek symbols	
λ	thermal conductivity (W/mk)
α_h	heat transfer coefficient at inner surface (W/m^{2}K)
α_e	heat transfer coefficient at outer surface (W/m^{2}K)
Subscripts	
g	gas
s	solid
wi	wall inside
wo	wall outside

1. Introduction

The introduction of fuel cell vehicles (FCV) to public within few years faces lot of challenges. Designing of hydrogen storage tanks as well as fueling systems are the most remarkable items in these challenges. Hydrogen has a very high energy content by weight (about three times more than gasoline), but it has a very low energy content by volume (about four times less than gasoline). This makes hydrogen a challenge to store, particularly within the size and weight constraints of a vehicle. Moreover, Developing safe, reliable, compact, and cost-effective hydrogen storage technologies is one of the most technically challenging barriers to the widespread use of hydrogen as a form of energy. To be competitive with conventional vehicles, hydrogen-powered cars must be able to travel more than 300 miles between fills. This is another challenging goal because hydrogen has physical characteristics that make it difficult to store in large quantities without taking up a significant amount of space.

Lot of efforts have been taken for designing the storage tanks for FCV system. Until now, a CFRP composite material for constructing the pressure vessel for storing hydrogen is widely familiar. CFRP is very strong and light weight. However, it is necessary to keep the material temperature below 85°C under a regulation. Since it is possible to exceed this temperature as a result of the compression work in the filling process, it is desirable to be able to predict the temperature rise prior to commencing refuelling. However, controlling the temperature is one of the key technologies, because the temperature of the hydrogen during filling up to 70 MPa (which is designed to be needed) rises the temperature beyond the temperature limit of CFRP tank. Particularly, in the fast filling system up to 70 MPa in hot summer days, the temperature of the tank can go beyond the temperature limit easily (Khan et al., 2009). Therefore, the reserved hydrogen should be kept cool or the filling system of hydrogen should take enough precautionary measures so that the hydrogen temperature does not exceed 85°C.

Therefore, simulations have been conducted for optimizing the filling system of hydrogen fuel to the storage tank. Different filling conditions, particularly for different heat transfer coefficients of hydrogen gas for grasping the temperature behavior in the hydrogen storage tank have been adopted in the simulation. Experimental data of JARI has been utilized for comparing the simulation results as well.

2. Configuration analysis

2.1. Storage vessel

Three types of hydrogen storage vessels with different volumes have been considered. However, only one test vessel has been analyzed for optimizing the filling prediction. The wall materials of each test vessel were considered CFRP composite materials along with liner material as aluminium (Al). The schematic configuration of a CFRP hydrogen storage vessel is shown in Fig. 1(a) and its diagonal cross-sectional view is shown in Fig. 1(b). As shown in the figure, one control valve

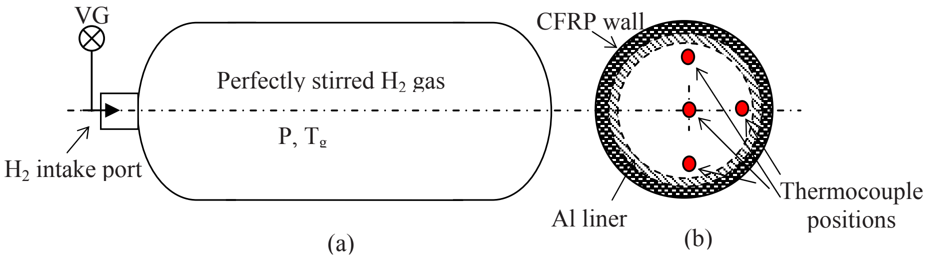


Fig. 1. (a) Schematic of H_2 gas reservoir; (b) cross-section of the reservoir and the thermocouple positions.

Table 1: Vessel specifications and wall properties

Specifications of hydrogen vessel			
Length (m)	O. Diameter (m)	Wall thickness (m)	
0.832	0.4	0.017	
Liner Parameters			
Thickness (m)	Th. Conductivity (W/mk)	Sp. Heat (J/kgK)	Density (kg/m^3)
0.003	180.0	896.0	2700.0
CFRP parameters			
Thickness (m)	Th. Conductivity (W/mk)	Sp. Heat (J/kgK)	Density (kg/m^3)
0.015	1.14	1075.0	1374.0

(VG) is installed at the inlet port of the storage tank for measuring the inlet temperature and inlet pressure of hydrogen gas. The gas pressure and gas temperature inside the vessel are mentioned as P and T_g respectively. The locations of temperature sensors (thermocouple) for getting the sample data in JARI experiments are shown in the figure as well. The wall materials of the tank which influence largely in heat transfer procedure are standardized in the simulation by taking their standard thermal properties as shown in Table 1. Details of the experimental apparatus and procedures of JARI 's experiment is not included here. Only the parameters related to the simulation are mentioned in this paper.

2.2. Filling system

In simulation process, one hydrogen storage vessel (D34L: Japan Automobile Research Institute (JARI) tank) has been used to verify the optimization technique with different filling conditions. The thermal characteristics due to filling system have been analyzed for the examined vessel. The supply system is divided into three storage system having vessels initially at 44 MPa and 87.5 MPa. This configuration is suitable for charging test vessels to 70 MPa. For 35 MPa runs only storage 1 has been required. Similarly for rising higher pressure than 35 MPa, other storages are used. Major objectives of the simulation were ascertained for optimizing the hydrogen filling system to the vessel based on several conditions; such as (i) space average gas temperature at all points in time during and after charging, (ii) final mass of hydrogen in the vessel, (iii) temperature of the wall inside surface, liner/CFRP interface and outside wall surface, (iv) temperature distribution in the wall at a desired point in time. The inlet of the flow system to the vessel plays an important role for the valve system and supply line (due to the negative Joule-Thomson effects). Furthermore, the inertial and compression effects of hydrogen flow in the supply line influence in rising gas temperature in the tank as well. The radiation loss in the flow line does not considered in the calculation, because it is considered as perfectly insulated.

2.3. Thermodynamic modelling

In modelling the system, the geometry of the vessel is simplified to a cylinder for illustration purposes. Although, the program does not care about the shape of the vessel, only the volume and the inside surface area are considered important for simulating temperature rise in filling system. For simplicity, it is assumed that the hydrogen gas is well stirred within the vessel so that the values of gas density and specific internal energy throughout the vessel inside remain constant. Moreover, it is also assumed that the hydrogen supply volume is much larger than the vessel, so that the supply properties do not change during charging. As it is mentioned earlier that the flow work is done as hydrogen is compressed inside the vessel in filling, it causes temperature rise and heat is transferred to the wall by convection. Therefore, finally, the wall temperature rises and finally heat is lost to the surroundings by convection process. In order to evaluate this phenomena, heat transfer rate is calculated from following simple formula (Monde et al., 2007).

$$\frac{dQ}{dt} = -A\lambda \left.\frac{\partial T_s}{\partial t}\right|_{x=0} \tag{1}$$

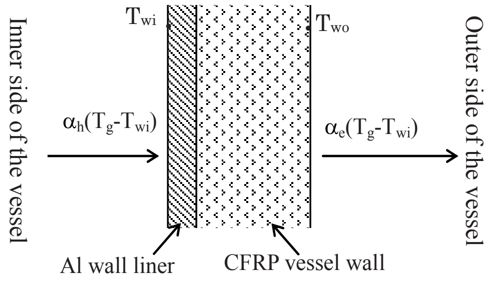


Fig. 2. Schematic figure of vessel wall and its thermodynamic modelling

where, λ indicates the thermal conductivity, A indicates the internal surface area of the vessel. The parametric notation, x indicates the argument in the x-direction across the thickness of the wall. As the combined wall of the vessel is assumed as one-dimensional solid, its temperature is indicated by T_S . Therefore, to simplify the above equation and to determine the wall temperature, the unsteady heat conduction equation can be applied by the following boundary conditions (Woodfield et al., 2008).

$$-\lambda_s \left.\frac{\partial T_s}{\partial x}\right|_{x=0} = \alpha_h \left(T_g - T_s\big|_{x=0}\right) \tag{2}$$

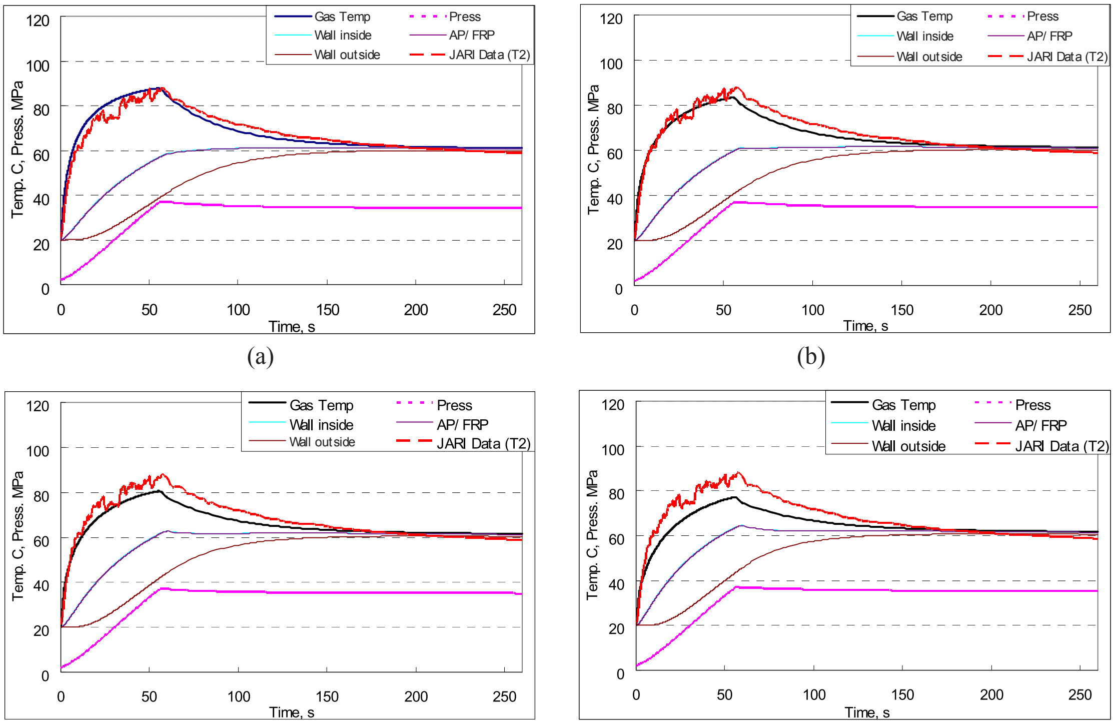
$$-\lambda_s \left.\frac{\partial T_s}{\partial x}\right|_{x=l} = \alpha_e \left(T_s\big|_{x=l} - T_{wo}\right) \tag{3}$$

In the above equation, the suffices, s indicates the parameters of solids (combined vessel wall). Moreover, as the gas is assumed as well stirred, it is considered here as, $T_{wi} \equiv T_s\big|_{x=0}$, where T_{wi} indicates the wall inside temperature. The wall outside temperature is indicated by T_{wo}. Moreover, α_h, α_e indicate the heat transfer coefficients at inner and outer surfaces respectively and l indicates the total thickness of the wall. This thermodynamic model is shown schematically in Fig. 2. One important consideration in the present modelling is that there is zero contact resistance between the surfaces of aluminium liner and CFRP vessel wall.

3. Results of thermal characterization of CFRP hydrogen vessel

3.1 Performance analysis in temperature estimation

The temperature rise of hydrogen gas inside the vessel as well as the vessel wall due to the filling system as described above is shown in Fig. 3. The estimation of this temperature rise of the storage vessel is predicted by using the software developed by Monde et al. 2007. The calculation is performed based on the energy balance as described above. The measured pressure in the tank during continuous filling to 35 MPa is also shown in the figure. After the vessel has been charged the determination of pressure is necessary and in the present model, it is done based on the Lee-Kester formulation. Furthermore, it is considered that the pressure changes linearly until it reaches to the final pressure (35 MPa). After getting its final pressure (when closing the inlet valve), the pressure remains constant. When the gas attains its final pressure, the temperature is also raised to its ultimate position. In the figure, it is found that gas temperature is raised to around 80 °C from its initial temperature at around 20 °C. As the gas temperature increases, the heat transfer occurs from gas to vessel wall and wall to the atmosphere as explained in the above model. The estimated result is also compared with the JARI experimental data which shows a clear agreement with the estimation process by the developed software. It is also mentioned that the temperature rise of the reservoir varies remarkably based on the filling time. For the quick filling, temperature rises largely compared with the slow filling (Khan et al. 2009). Moreover, there are a lot of parameters that influences the rise of temperature of the vessel as mentioned in the following sub-sections.



(a) (b)

(c) (d)

Fig. 3. Temperature profile of test vessel for 60 seconds fill. JARI Data is for comparison of estimated data. Heat transfer coefficients in W/m^{2}K (gas to liner-liner to CFRP-CFRP to outside) are (a) 300-250-4.5, (b) 400-250-4.5, (c) 500-250-4.5, (d) 700-250-4.5.

3.2 Effect of heat transfer coefficient on temperature rise

The influence of temperature rise of the hydrogen gas inside the vessel on various heat transfer coefficient is also verified with the developed software. The results are shown in Figs. 3(a) – 3(d). It is found in the analysis that the calculation result of hydrogen gas at the center of the vessel largely differs for different heat transfer coefficient keeping other test conditions (Table 1) same. Furthermore, as mentioned earlier that the CFRP vessel is the most suitable consideration to the automobile companies, in the present simulation, only the value of heat transfer coefficient of gas to wall (liner) is investigated and therefore, the value of heat transfer coefficients for the vessel wall (liner and CFRP) have been kept constant. In results (Fig 3) it is found that the temperature rising of the hydrogen gas inside the vessel can be controlled effectively (around 10 – 15 °C reduction as shown in the present simulation results) reduced by controlling the heat transfer coefficient of gas to wall. Thus, it would be a considerable thinking for the reduction of the compression works of the filling process for adopting the advantages of the present results.

4. Discussion

In the present paper the thermal characteristics of hydrogen vessel is presented only for one type of storage vessel. However, the varied thermal properties for various storage vessels affect the characteristics of temperature rise as well. For example, the nozzle effect plays an important role in the initial temperature of hydrogen gas as mentioned earlier. Moreover, the filling time is another factor for controlling the temperature rise inside the vessel (Khan et al., 2009). The heat transfer coefficient for the outside of the tank (α_e) is set to 4.5 W/m^{2}K for all calculations, although its value has almost no effect on the present heat transfer analysis. Furthermore, it should be noted that the available temperature does not correspond to the actual gas temperature at the tank inlet, as the temperature sensor by which the temperature has been measured in the experiment, has been located far from the lank inlet. Unfortunately, no information is available about the data that how far the sensor has been placed.

It is considered in the present calculation that the hydrogen vessel is well stirred. However, Woodfield et al. 2007 mentioned that during the filling of hydrogen the heat transfer coefficient varies in an wide range depending on filling mass flow rate and thus that value is strongly influenced by the location and this effect increases as the location becomes farther from the inlet. On the other hand, when the hydrogen is discharged the heat transfer coefficient is almost independent of the location and its value continuously decreases as the mass flow rate decreases. Therefore, although, the mass flow rate is almost identical in filling and discharging, the heat transfer coefficient behaves with different trends. Thus it is found in the present calculations temperature rise is greatly influenced by this thermal properties. Another important factor in this regard is that heat transfer coefficients are quite different depending on not only the position but also on the time after the filling. In the present model it is assumed that αh is constant for the total filling time. However, practically it varies with the mass flow rate and the changes of gas pressure inside the vessel. Therefore, carefulness is necessary, although, a suitable constant value of heat transfer coefficient is considered in the present model for calculating the temperature rise in gas as well as in vessel wall.

5. Conclusions

Thermal characteristics of hydrogen gas of the storage vessel as well as of the vessel wall have been analyzed successfully by the developed software (Monde et al. 2007). The parameters adopted in the present simulation are considered based on different experimental and simulation data conducted at Saga University as well as at JARI. From the analysis it is clearly understood that for the safety of CFRP hydrogen storage vessel, controlling of rising temperature in the filling process is an important factor and thus, the adjustment of the heat transfer coefficient of filling gas can play an influential role for that purpose.

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References

[1] Khan Md. T. I, Monde M, Setoguchi T. Hydrogen gas filling into an actual tank at high pressure and optimization of its thermal characteristics, J. Thermal Science 2009; 18: 235-240.

[2] Monde, M, Mitsutake Y, Woodfield P. L, Maruyama S. Characteristics of heat transfer and temperature rise of hydrogen during Rapid Hydrogen Filling at High Pressure. J. Heat Transfer – Asia Research 2007; 36: 13-27.

[3] Woodfield P. L, Monde M, Takano T. Heat transfer characteristics for practical hydrogen pressure vessels being filled at high pressure. J. Therm Sci Tech 2008; 3(2):241-53.

[4] Woodfield P. L, Monde M, Mitsutake Y. Measurement of average heat transfer coefficients in high-pressure vessel during charging with hydrogen, nitrogen or argon gas. J Therm Science Eng 2007; 2(2):180-90