

Understanding of Thermal Characteristics of Fueling Hydrogen High Pressure Tanks and Governing Parameters

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ABSTRACT

For safe and fast refueling hydrogen to fuel cell vehicles (FCVs) at hydrogen refueling stations (HRSs), a refueling protocol is under discussion at SAE J2601 to be a global standard. In order to realize such a standard, we have to estimate the relation between gas temperature and pressure during a refueling and for an accurate estimation we have to correctly understand the thermal characteristics of hydrogen tank.

Fast refueling test data has been offered by BMW-Powertech, some test cases have been analyzed by a simulation model developed by Monde et al. It reveals that the hydrogen temperature at the end of refueling does not exceed 85 °C for these analyzed cases. The effect of the pressure drop between storage bank and hydrogen tank was negligible small on the gas temperature at the end of refueling, although the gas temperature shows different profile depending on the pressure drop. The simulation results of the model in this study were in good agreement with the gas temperature profile obtained by BMW-Powertech test. Current analysis shows the total heat loss to the wall becomes smaller than 10 % of the total inlet enthalpy.

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INTRODUCTION

The first phase of commercial fuel cell vehicles (FCVs) will be introduced to the market from 2015 in Japan, Germany and USA. Corresponding to their activities, the Japanese and German governments have started financially supporting construction of about 100 hydrogen stations in four major economical areas in Japan and about 50 stations along major automotive lanes in German. In order to successfully complete this project by 2015, one has to understand the thermal characteristics of hydrogen tank during refueling process up to 70 MPa Nominal Working Pressure (NWP) and at full-time within 3 minutes, because the temperature of a carbon fiber reinforced plastic (CFRP) composite tank should be limited to 85 °C due to a current safety standards.

One of the authors [1] has developed software to estimate how temperature rises during filling hydrogen up to 70 MPa Nominal Working Pressure (NWP) into the tank. It has been recently verified that the estimated temperatures are in good agreement with the measured temperatures in the filling tests which had been done by Japanese Organizations [1]. The simulation software has been used to build a protocol, utilizing a Lookup Table, with the defined a procedure of the hydrogen refueling into the on-board tank according to SAE

J2601 discussions. SAE J2601 allows data from the vehicle storage through infrared (IRDA) data transfer between the vehicle (FCV) and the station, to allow for a more precise temperature compensation which ensures a high state of charge and safe hydrogen refueling. In order to effectively utilize the IRDA data into a filling protocol, the parameters concerning the temperature rise during filling hydrogen should be made clear. As a result, the improved protocol with the IRDA communication makes it possible not only to fill hydrogen into the FCV tank safely and quickly but also to reduce costs of the station construction and maintenance, due to lower requirements for precooling, for instance. The IRDA communications protocol may make the filling procedure flexible, in the future beyond the present state-of-the art. constant pressure rise filling procedure.

The present paper first focuses on 6.3 kg 70 MPa Type IV vessel and determines the pressure ramp rate for some representative cases to complete the refueling upto 87.5 MPa at a temperature lower than 85 °C within 3 minutes. The simulation conditions are given by Table 1. The way in which heat is transferred into the tank wall during the filling will be analyzed together with BMW-Powertech data. Finally, the objectives of the paper help us to correctly understand the heat transfer and the inlet enthalpy.

THERMODYNAMIC MODEL FOR HYDROGEN REFUELING

The refueling process [1, 2, 3] of the tank follows the first law of thermodynamics for a semi-open system and is given in a form of time derivative as follows:

$$dU / dt = dQ / dt + h_{in} m_{in} \quad (1)$$

where U is the total internal energy of the tank, Q is the heat added to the system from the surroundings and h_{in} is the enthalpy at the inlet and m_{in} is the rate of refueling mass to the tank at a moment.

After integrating Eq.(1), one can obtain as:

$$U(p(t), T(t)) - U(p_o, T_o) = Q(t) + \int_0^t m_{in} h_{in} dt \quad (2)$$

The amount of internal energy will be determined by calculating how amounts of the heat, Q and also the supplied enthalpy are added during refueling hydrogen into the tank. The amount of the supplied enthalpy can be operated by the hydrogen station which can control a filling mass rate, m_{in} and temperature T_{in} of hydrogen. The heat strongly depends on hydrogen flow condition in the tank, the tank specification and also thermal properties of tank wall.

Therefore, if all needed parameters related to refueling procedure as listed in Table 1 and to tank specifications as listed in Table 2 are provided, the internal energy at a time after starting the hydrogen refueling can be determined from Eq.(2), resulting into the hydrogen temperature after a set duration. Woodfield [2] et al. developed their software to analyze Eq. (1) numerically. Monde et al. [1] verified a validation of their software by showing a good agreement between the calculated temperatures and the measured temperatures in a Japan Automobile Research Institute (JARI) and Japan Hydrogen & Fuel Cell Demonstration Project (JHFC) refueling tests.

TEMPERATURE RISE AND HEAT LOSS

A current on-board hydrogen tank is connected to a dispenser with a pipe line as shown in Fig.1. The pressure, p_2 at the position 2 may equal to the pressure in the tank, while it is always lower than the pressure, p_1 at the position 1, that is $\Delta p = (p_1 - p_2) > 0$. The hydrogen temperature in the tank is basically evaluated by the software based on Eq.(2) using the pressure, $p_{in} = p_2$ and the temperature, $T_{in} = T_2$ at the position 2.

Temperature Rise During Refueling in Simulation

The temperature rise during the hydrogen refueling can be calculated from Eq. (2) using the Monde et al. model and

their simulation software. The software requires the related parameters as listed in Tables 1 and 2, which are estimated from a requirement that an average commercial FCV approximately 6 kg hydrogen to drive the FCV about 500 km and the refueling to FCV is completed within approx. 3 minutes. The thermal properties of liner and CFRP are, for example, chosen from the representative values which are obtained by the measurement of thermal properties for liner and CFRP used for a conventional tank in our laboratory. The pressure ramp rate is determined to satisfy the abovementioned requirements.

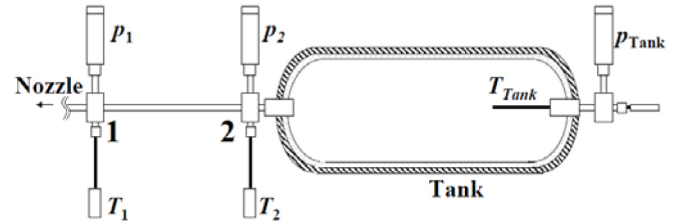


Figure 1. Schematic of tank and pipe line

Table 1. Simulation conditions for refueling

Ambient temp.	T_e	°C	0, 30
Initial temp.	T_0	°C	$T_0 = T_e + 15$
Inlet temp.	T_{in}	°C	$T_{in} > -33 : T_{in} = T_e - 6 \text{ t},$ $T_{in} \leq -33 : T_{in} = -33$
Inlet pressure	p_{in}	MPa	$\Delta p > 0$: Estimated loss $\Delta p = 0$: APRR = $(p_f - p_o)/t_f$
Initial pressure	p_0	MPa	2, 10

Table 2. Dimension and properties of tank

70MPa 1 - 7kg (6.3kg 70MPa Type IV)			
Internal volume	L	V	157
Internal liner surface	m ²	A	1.57
Internal diameter	m	D	0.476
Liner			
Wall thickness	mm	δ_1	5.07
Thermal conductivity	W/(mK)	λ_1	0.385
Spec. heat capacity	J/(kgK)	c_1	1584
Density	kg/m ³	ρ_1	945
CFRP			
Wall thickness	mm	δ_2	35.3
Thermal conductivity	W/(mK)	λ_2	0.74
Specific heat	J/(kgK)	c_2	1120
Density	kg/m ³	ρ_2	1494
Heat transfer coefficient			
Inside surface of liner	W/m ² K	α_{in}	443.6
Outside surface of CFRP	W/m ² K	α_{out}	4.5

Figure 2(a) shows the pressure changes at the positions 1 and 2 and also inlet temperature change during the hydrogen refueling for the case of ambient temperature, $T_e = 0$ °C. Figure 2(b) shows the rises in the hydrogen temperature for the cases without the pressure loss, $\Delta p = 0$ and with its loss.

$\Delta p > 0$, respectively, when the hydrogen is refueled at the same temperature between positions 1 and 2, into the tank with dimension and properties listed in Table 2 and also the corresponding temperature changes of the inner surface wall.

It is found from Fig. 2 that the temperature histories during the hydrogen refueling become much different depending on whether the pressure loss is taken into account or not as shown in Fig. 2(a). The temperature at the end of refueling reaches the temperature lower than 85 °C. It may be worth to note that the final temperatures for both the cases merge the almost same one within the temperature difference of 1 K, that is, the pressure loss through the pipe line makes negligible small effect on the temperature rise, namely the increase in internal energy.

Figure 3(a) also shows the pressure changes at the positions 1 and 2 and also inlet temperature change during the hydrogen refueling for the other case of ambient temperature, $T_e = 30$ °C. Figure 3(b) also shows the rises in the hydrogen temperature for two cases of $\Delta p = 0$ and $\Delta p > 0$ when the hydrogen is refueled the tank given by Table 2.

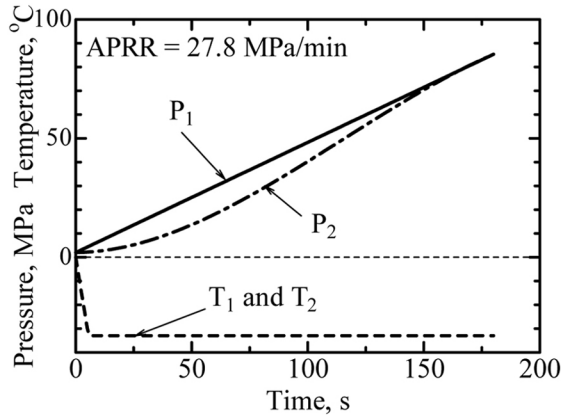


Figure 2(a). Initial conditions for hydrogen refueling ($p_o = 2$ MPa and $T_e = 0$ °C)

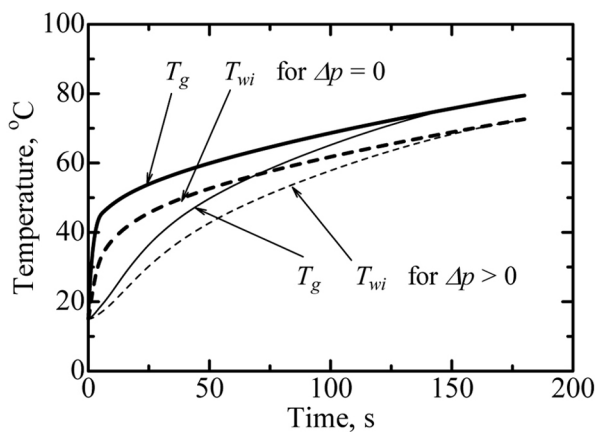


Figure 2(b). Temperature change of hydrogen in tank and inner surface wall for $\Delta p = 0$ and $\Delta p > 0$ ($p_o = 2$ MPa and $T_e = 0$ °C)

On comparison with Figs. 2(b) and 3(b), one can deduce, that the temperature history for the case of $\Delta p = 0$ appear significantly different trend within 20 second after the hydrogen refueling starts. The sharp increase in the temperature for the case of $T_e = 30$ °C seems to be caused by the Joule Thomson effect, because very large pressure drop occurs between the inlet pressure and the pressure in the tank, while for the case of $T_e = 0$ °C, the temperature rise due to the Joule Thomson effect may be traded off by the bulk temperature increase. The Joule Thomson effect disappears soon with an increase in pressure in the tank. After 10 sec, the bulk temperature may be decreased by the refueling of precooled hydrogen, being much lower than the initial temperature.

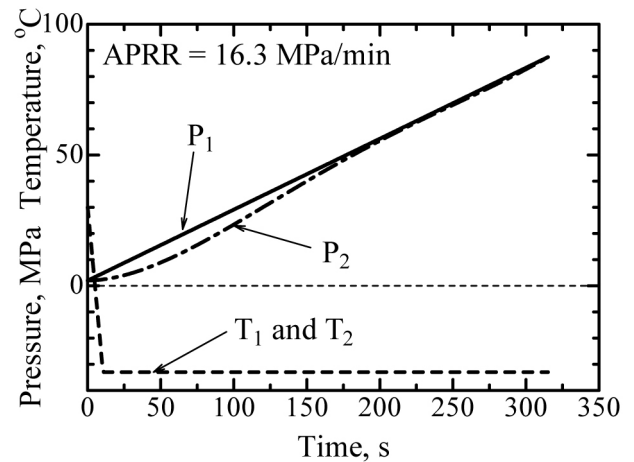


Figure 3(a). Initial conditions for hydrogen refueling ($p_o = 2$ MPa and $T_e = 30$ °C)

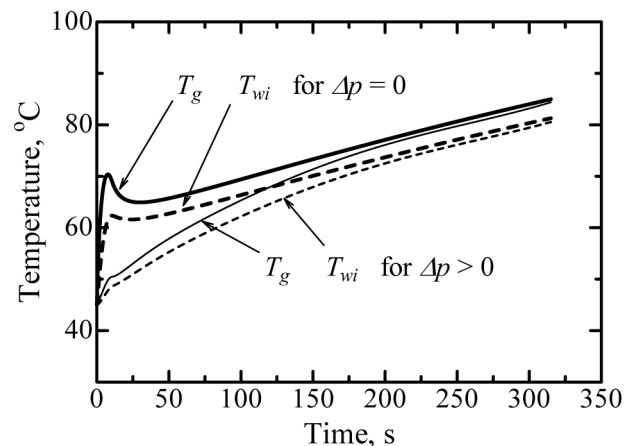


Figure 3(b). Temperature change of hydrogen in tank and inner surface wall for $\Delta p = 0$ and $\Delta p > 0$ ($p_o = 2$ MPa and $T_e = 30$ °C)