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Estimation of temperature change in practical hydrogen pressure tanks being filled at high pressures of 35 and 70 MPa

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ABSTRACT

Some complete experimental data sets, not only on the hydrogen temperature within the tank during filling, but also on the supplied temperature and pressure from the station have been opened for analysis of the temperature change with time. The data were independently obtained for 6 different conditions and have been analyzed and checked to validate the Monde et al. model. It is found that the measured temperatures are well predicted using the software based on the model and the heat loss during filling with hydrogen is also well predicted, if a suitable heat transfer coefficient is adopted.

1. Introduction

Recently, it was decided that the first phase of commercial fuel cell vehicles (FCV) will be introduced to the market from 2015 as the first phase by Japanese automotive companies [1,2]. Corresponding to their activities, the Japanese government has started financially supporting construction of about 100 hydrogen stations in four major economical areas in Japan. In order to successfully complete this project by 2015, one has to understand the temperature characteristics of hydrogen in the tanks. Temperature control is as one of the key technologies, because the temperature of the hydrogen during filling hydrogen up to 70 MPa into the carbon fiber reinforced plastic (CFRP) composite tank should be limited to lower than 85 °C due to a safety regulation. More recently, filling tests have been extensively executed to keep this regulation for several different kinds of tanks. Some of the results, which have been measured during filling hydrogen into the tank by private companies are gradually entering the open literature for analysis of the temperature characteristics. In other countries, there are also many research projects on hydrogen storage at high pressure in concert with Japanese activities as well as overseas automotive activities.

According to experimental results, when a hydrogen vessel is filled on a hot summer's day and/or using a fast filling procedure up to 70 MPa, unfortunately, the temperature in the tank can go beyond 85 °C. Therefore, the supplied hydrogen

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should be cooled so as not to exceed the hydrogen temperature of 85 °C and an accurate understanding of temperature behavior is required from a better understand and safety points of view.

With the above circumstances in mind, many experiments and numerical studies have been conducted to grasp the temperature behavior in the tank during fast filling with hydrogen fast into the tank at high pressure [3–12]. Monde et al. [3] measured the temperature change during filling of a small tank with hydrogen and nitrogen to a pressure of 30 MPa and then showed the temperature distribution and effects of the filling time and location of the nozzle on the temperature distribution. In addition, they showed that the highest temperature hydrogen appears near the opposite end of the tank to the nozzle and how the heat transfer coefficient changes with mass flow rate was quantified. Monde et al. [3,4] proposed a thermodynamic model together with heat transfer from hydrogen into the tank wall, by which the measured temperatures during fast fill study up to 35 and 70 MPa conducted at Powertech in Canada were analyzed [4]. Their study yielded agreement in the trends of temperature behavior for both 35 and 70 MPa between the measured and estimated ones, but poor quantitative agreement for 70 MPa. The poor agreement at 70 MPa may be caused by a lack of thermal properties and specifications of the tank.

Dicken and Merida [5] conducted an elaborate experiment by arranging 63 thermocouples distributed throughout the tank to capture the temperature profile. They showed that the temperature field within the cylinder was significantly stratified in the vertical direction for slower fills and then, the except for the region near the wall and the injected zone, the temperature seemed to change almost uniformly. Dicken and Merida [6] proposed a numerical model based on symmetric flow where the effects of gravitational and buoyancy forces are ignored in comparison with the velocity effect. The temperature estimated by their model seems to be in poor agreement with the measured values. Liu et al. [7] also measured the temperature change during refueling hydrogen vessels and showed the effects of initial pressure and mass velocity on the temperature rise.

Heitsch et al. [8] numerically simulated the fast filling of hydrogen tanks using the CFD code CFX and compared the measured temperature rise by Dicken and Merida [5] with the estimated one during the increase in mass. It is hard to say that the agreement between them is good for a fill time of 40 s. Zhao et al. [9] also carried out numerical simulation on temperature rise and showed that the estimated temperature is in agreement with the measured temperature rise with time, although some small difference in trend was also apparent.

Yang [10] theoretically analyzed the refueling process for three different conditions, namely, adiabatic, isothermal and diathermal. The heat transfer from hydrogen into the wall was not discussed in detail. The trends in temperature rise are shown only for different boundary conditions.

Maus et al. [11] and Zheng et al. [12] discussed a procedure to refuel hydrogen at a practical hydrogen station.

Incidentally, New Energy Development Organization (NEDO) [1,2] in Japan has financially supported us in order to expand a FCV society smoothly, and in particular to construct several hydrogen stations, what is required to refuel hydrogen into the FCV is safely becoming clear. Through Japan Hydrogen & Fuel Cell Demonstration Project (JHFC) and NEDO activities including of support of automotive companies, the measured data not only of the hydrogen temperature within the tank during filling with hydrogen but also on the supplied temperature and pressure from the station have been gradually opened for analysis of the temperature change with time. The present paper analyzes these available data to validate the Monde et al. model [3,4] and then shows a comparison between the estimated and measured temperatures. In addition, what kinds of physical parameters mainly influence the temperature rise will be discussed.

2. Thermodynamic model for refueling of hydrogen tank

The refueling process of the tank surely obeys the first law of thermodynamics for a semi-open system and is given without any work in a form of time derivative as follows:

$$dU/dt = dQ/dt + h_{in} dm_{in}/dt \tag{1}$$

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 supplied mass to the tank.

In order to solve Eq. (1), one has to evaluate the heat transfer rate dQ/dt between hydrogen and the tank and the internal energy throughout the tank, while the value of $h_{in} dm_{in}/dt$ will be calculated from the refueling condition at the station. The value of dQ/dt can be given as:

$$\frac{dQ}{dt} = \int_A -\lambda \frac{\partial T_s}{\partial x}\bigg|_{x=0} dA = \int_A \alpha_h (T_w - T_g) dA \tag{2}$$

where T_g is the local temperature within the tank, T_s is the solid temperature, T_w is the wall surface temperature, λ is thermal conductivity, α_h is heat transfer coefficient, x is the argument in the x-direction across the thickness of wall, and A is the internal tank surface area. The total internal energy is also given using the hydrogen density ρ_g and specific internal energy u_g as:

$$\frac{dU}{dt} = \frac{d}{dt}\int_V \rho_g u(p, T_g) dV \tag{3}$$

where V is the total inside volume of the tank. The density in the tank is given by the real-gas equation of state specified in Eq. (4). The compressibility, Z, is calculated using a polynomial fit to hydrogen gas data generated the Lee–Kesler method [14]. This data agreed well with tabulated compressibility data [15] for hydrogen in the range of temperatures considered in this study.

$$\rho(P, T_g) = \frac{P}{Z(P, T_g) R T_g} \tag{4}$$

The specific internal energy is also calculated from the hydrogen gas data [14].