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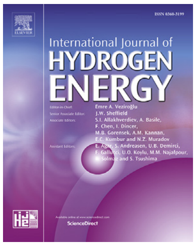

Prediction of transient temperature of hydrogen flowing from pre-cooler of refueling station to inlet of vehicle tank

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ABSTRACT

A thermodynamic analytical approach is proposed to obtain the transient temperature rise of hydrogen when pre-cooled hydrogen is heated through filling equipment at a refueling station. In this approach, the filling equipment is assumed to be a simple and straight pipeline, and the heat balance based on the thermodynamics for hydrogen flowing in the pipeline is analyzed. The internal surface temperature of the pipeline wall is required to calculate the heat flux into hydrogen. Therefore, we propose a solution to obtain the temperature distribution in the pipeline wall when hydrogen with lower temperature than the pipeline flows unsteadily. Based on the proposed solution, we calculate the heat flux and acquire the hydrogen temperature. The hydrogen temperatures predicted by this approach are compared with experimental data for the temperature rise of hydrogen heated through actual filling equipment, and a good agreement is shown. Thus, we show that this approach is useful for simulating the temperature rise of hydrogen flowing in the filling equipment.

Introduction

In recent years, hydrogen fuel cell vehicles (FCVs) has been commercially available, and the number of hydrogen refueling stations (HRSs) has been increased. Safety management of FCVs and HRSs is highly importance because of dealing with high-pressure hydrogen up to 87.5 MPa, and many studies have been performed for safety operations of them [1–6]. In the process of filling high-pressure hydrogen to FCVs, the temperature change in the FCV tanks is concerned not to exceed the permissible maximum temperature of 85 °C by the adiabatic compression of hydrogen [7,8]. Monde et al. [9–11] derived an analytical approach to predict a hydrogen temperature in a FCV tank during fast fillings based on the thermodynamic energy balance of the FCV tank. Galassi et al. [12] studied hydrogen temperatures in a FCV tank during fast fillings of hydrogen at various inlet conditions of the tank. Due to these studies, many findings with regard to safety in hydrogen filling were obtained. In particular, the importance of pre-

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cooled hydrogen to maintain a hydrogen temperature in a FCV tank below the permissible maximum temperature (85.0 °C) was widely accepted. Furthermore, the effect of the pre-cooling temperature on the temperature in a FCV tank is still evaluated to refuel hydrogen more rapidly and safely [13,14]. However, most of the previous researches on the effect of the pre-cooling temperature are only focused on the FCV tanks, and the thermal behavior of pre-cooled high-pressure hydrogen flowing in the filling equipment, which is the path between the pre-cooler and FCV tank, has not been evaluated. Consequently, the present filling equipment at HRSs is empirically designed. In this study, a thermodynamic analytical approach is presented to predict the transient temperature rise of pre-cooled high-pressure hydrogen which is heated through the filling equipment with an environmental temperature. In this approach, we use a simple and straight pipeline as the analytical model. First, we propose a solution to obtain temperature distribution in the pipeline wall. Due to the solution, the internal surface temperature of the pipeline wall can be obtained, and the heat flux into hydrogen is calculated. Afterward, we investigate the heat balance in the pipeline based on the heat flux, the inflow enthalpy and outflow enthalpy, and therefore acquire the hydrogen temperature. Subsequently, we show that the hydrogen temperatures predicted by this approach agree with experimental results. Thus, the presented theoretical analysis is simple and given based on the thermodynamics, and contributes to widen the degree of freedom in designing the filling equipment instead of conventional empirical estimations.

Calculation methods, models, and conditions

Governing equations for temperature of hydrogen heated through pipe

The heat balance of hydrogen in a short length pipe is described in Fig. 1, when hydrogen with lower temperature than the pipe passes through the pipe. A governing equation for hydrogen in the pipe is written as:

$$\frac{d}{dt}\left(m_{\text{gas}}u_{\text{gas}}\right) = m_{\text{in}}h_{\text{in}} - m_{\text{out}}h_{\text{out}} + q_{\text{in}}A \tag{1}$$

where m_{gas} is the hydrogen mass, u_{gas} is the specific internal energy, m_{in} and m_{out} are the mass flow rates, h_{in} and h_{out} are the specific enthalpies, q_{in} is the heat flux transferred through the pipe, and A is the internal surface area. In calculating the heat balance, the flow field in the pipe is presumed to be uniform regardless of any positions in the pipe. Additionally, the hydrogen temperature and pressure are assumed to be uniform irrespective of the position in the radial and flow directions. In the proposed analytical approach, the heat balance was calculated under the assumptions.

In order to evaluate the heat flux, q_{in}, it is necessary to determine the internal surface temperature of the pipe. The temperature is derived by solving the heat conduction equation for the pipe wall as follows:

$$\frac{\partial T}{\partial t} = a\left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r}\right) \tag{2}$$

The symbol T is the temperature in the pipe wall, t is the time, a is the thermal diffusivity, and r is the position in radial direction. The boundary conditions for the pipe wall in Equation (2) are given as:

$$q_{\text{in}} = -\lambda\left.\frac{\partial T}{\partial r}\right|_{r=r_{\text{in}}} = \alpha_{\text{in}}\left(T_{\text{gas}} - T|_{r=r_{\text{in}}}\right) \tag{3}$$

$$q_{\text{out}} = \alpha_{\text{out}}\left(T|_{r=r_{\text{out}}} - T_{\text{amb}}\right) \tag{4}$$

where T_{amb} is the environmental temperature, λ is the thermal conductivity of the pipe, α_{in} and α_{out} are the heat transfer coefficients for the inner and outer surfaces of the pipe. Only the heat transfer coefficient α_{in} was taken as a variable, which was calculated as follows [15]:

$$\alpha_{\text{in}} = 5.0 + 0.012\text{Re}^{0.83}(\text{Pr} + 0.29) \tag{5}$$

The solution of Equation (2) is already derived by Carslaw et al. [16], as shown in Appendix A (The details on the solution are given in Appendix A.). However, the solution in Appendix A is valid only for a steady flow. Mass flow rate during refueling at a HRS is approximately changing between 10 g/s and 50 g/s. Thus, we need to modify the transition term (second term of the solution in Appendix A) of the solution to adapt to the unsteady flow. The transition term strongly depends on the Fourier number including the eigenvalue p_n ($n = 1, 2, 3, \ldots$). Each eigenvalue is a function of a mass flow rate. Within the range of the mass flow rate up to 50 g/s, the first eigenvalue approximately changes from 0.4 to 0.9 as shown in Fig. 2. While the supplied hydrogen has unsteady and small mass flow rate, the first eigenvalue changes considerably. We found that the change of the first eigenvalue has a large effect on the Fourier number. Therefore, we modified the solution in

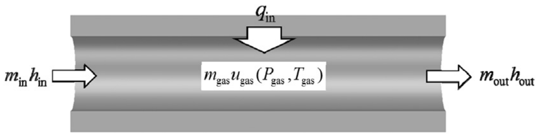

Fig. 1 – Schematic diagram for deriving hydrogen temperature.

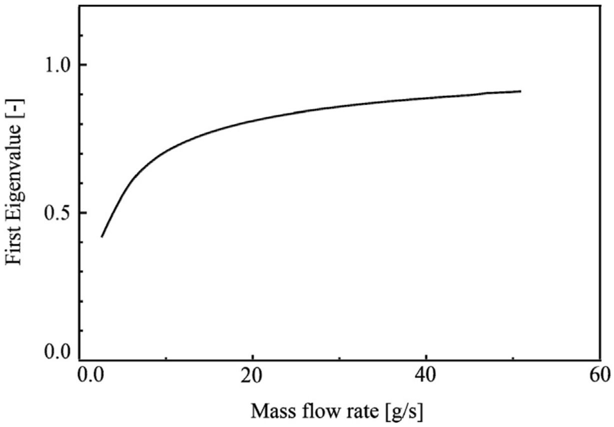

Fig. 2 – First eigenvalue and mass flow rate when environmental temperature is 0.0 °C.

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