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Determining hydrogen pre-cooling temperature from refueling parameters

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ABSTRACT

Compressed hydrogen storage has a requirement on the temperature: for safety reasons, the final gas temperature is not allowed to exceed 85 °C during filling. However, due to the short time and the fast filling rate in practice, the final gas temperature rises sharply. To solve the issue, the hydrogen could be pre-cooled sometimes, but setting the pre-cooling hydrogen temperature becomes a critical problem, we need to know whether the inflow hydrogen needs to be pre-cooled and what the pre-cooling temperature it should be. This paper proposes a new analytical solution of pre-cooling hydrogen temperature from a simplified lumped parameter model. The effects of initial temperature, initial pressure and the filling time on the inflow hydrogen temperature are studied, and three sets of equations are proposed correspondingly. Further we use these equations to fit the published reference data, the fittings show good agreement. The occasions where the hydrogen needs to be pre-cooled are presented. We suppose this study not only helps to choose the pre-cooling hydrogen temperature, but also ensure the safety during the hydrogen filling.

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Introduction

Hydrogen is acknowledged to be an alternative and a potential fuel in the future, and compressed hydrogen gas is widely used in fuel cell vehicles [1]. In practice, due to the short filling time and the fast filling rate, the final gas temperature rises rather quickly. But the carbon fiber reinforced plastic composite (CFRP) materials used in the system are sensitive to the temperature, when the temperature is too high, the materials would become brittle [2]. As a result of the materials' property, the compressed hydrogen storage has a requirement on the temperature: the final gas temperature is not allowed to exceed 85 °C during refueling [3].

To ensure the safety during the refueling, many researches have been done. Experiments were conducted by Liu, aiming to make clear the thermal behaviors of hydrogen storage [4]. A thermodynamic analysis was presented for a compressed gaseous hydrogen system [5]. Dicken et al. studied the influences of the total fill time and the initial mass

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Nomenclature

a_f	heat transfer coefficient between hydrogen and ambient fluid, $W/m^2/K$
A_s	internal surface area of tank, m^2
c_p	constant-pressure specific heat, J/kg/K
c_v	constant-volume specific heat, J/kg/K
h	specific enthalpy of hydrogen, J/kg
h_{in}	specific enthalpy of inflow H_2, J/kg
h_{out}	specific enthalpy of outflow H_2, J/kg
k_{p_0}	$k_{p_0} = T/(T_0 p_f)$
$k_{p_{0f}}$	$k_{p_{0f}} = T/T_0$
k_{p_f}	$k_{p_f} = Tp_0/T_0$
m	mass of hydrogen mass in tank, kg
m_0	initial hydrogen mass, kg
$\dot{m}$	mass flow rate, kg/s
$\dot{m}_{in}$	hydrogen mass inflow rate, kg/s
$\dot{m}_{out}$	hydrogen mass outflow rate, kg/s
p_0	initial pressure, MPa
p_{0f}	$p_{0f} = p_0/p_f$
p_f	final pressure, MPa
$\dot{Q}$	heat inflow rate, $\dot{Q} = a_f A_s(T_f - T)$, W
t	time variable or fill time, s
t^*	characteristic time, $t^* = m_0/\dot{m}$, s
T	temperature of hydrogen, K
T^*	characteristic temperature, K
T_0	initial temperature in tank, K
T_f	temperature of ambient fluid, K
T_∞	inflow or outflow temperature, K
u	specific internal energy, J/kg

Greek symbols

α	dimensionless heat transfer coefficient, $\alpha = a_f A_s/c_v \dot{m}$
γ	ratio of specific heats, $\gamma = c_p/c_v$
μ	fraction of initial mass, $\mu = m_0/m$
μ'	$\mu' = \mu^{1+\alpha}$
τ	dimensionless time, $\tau = t/t^*$

on the temperature distribution and the temperature rise, and a three-parameter formula was proposed [6]. An experiment was carried out to investigate the discharge cycle of a type III cylinder and a model was also presented [7]. The effect of mass flow rates and inlet gas temperatures on the end state of charge was measured by Cebolla et al., then a conclusion was drawn that the inlet gas temperature played an important role on the final state of charge [8].

Monde et al. [9] took two different ways to deal with the hydrogen gas and the tank wall, a lumped parameter model was used to describe the thermal behaviors of hydrogen gas in the tank and a one-dimensional model was used for tank wall. Their simulation results were proved to agree with the gas temperature profile obtained by BMW-Powertech tests [10]. Monde et al. derived approximate equations to predict the temperature of the pre-cooled hydrogen and the filling time for a practical vessel [11], the pre-cooled hydrogen temperature can be predicted by using a fitted formula with 36 coefficients and the filling time can be also known by the use of another fitted formula with 48 coefficients.

We developed the numerical solutions for the lumped parameter thermodynamic models of adsorptive and cryo-adsorptive hydrogen storage systems [12,13]. Based on the lumped parameter thermodynamic models, analytical solutions are developed for charge–discharge cycle of compression hydrogen storage system [14] and adsorption–desorption cycle of adsorptive hydrogen storage system [15]. The simple uniform formula is inspired by the concept of the rule of mixture and its weighted factors are obtained from the analytical solution of lumped parameter thermodynamics model. The analytical solution of the hydrogen temperature in the tank is used to fit the experimental temperatures [16,17]. Estimation of final hydrogen temperature from refueling parameters based on the rule of mixtures is simple and practical for controlling the maximum temperature and for ensuring hydrogen safety during fast filling process.

The SAE J2601 establishes the protocol and process limits for hydrogen fueling of light duty vehicles, it has been developed to meet the performance objectives under all practical conditions based on a look-up table approach [18,19] and MC Method [20,21]. The useful hydrogen fueling test data is available at http://www.h2protocol.com/h2-fueling-data/ [22]. These data would be used for further estimation of final hydrogen temperature or determination of pre-cooled hydrogen temperature.

In the research of the development of hydrogen storage system, in order to meet the requirement of the highest temperature limit (e.g. 85 °C), cooling the hydrogen in advance has been proved to be an applicable way. However, setting the pre-cooling hydrogen temperature has become a critical problem, which should not only ensure the final temperature of hydrogen not to exceed the corresponding limits, but also avoid making the pre-cooling temperature too low to waste energy. In this article, we fix the final temperature as the highest temperature limit (e.g. 85 °C), express the pre-cooling temperature T_∞ as the function of refueling parameters including initial temperature T_0, initial pressure p_0 and filling time t under different final pressures. For the three cases, the deduced equations are used to fit the reference data. The fittings show good agreement. Furthermore, the fitting result can be used for deciding whether the inflow hydrogen needs pre-cooling or not and how could it should be.

Model for determining hydrogen pre-cooling temperature

General mass and energy balance equations for charge/discharge processes of high pressure hydrogen gas into/from a tank are mostly written as [14].

$$\frac{dm}{dt} = \dot{m}_{in} - \dot{m}_{out} \tag{1}$$

$$\frac{d}{dt}(mu) = \dot{m}_{in} h_{in} - \dot{m}_{out} h_{out} + \dot{Q} \tag{2}$$

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