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Thermo-mechanical investigation of composite high-pressure hydrogen storage cylinder during fast filling

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ABSTRACT

The fast refueling process of hydrogen results in a significant temperature rise within the composite hydrogen storage cylinder, which may decrease the cylinder state of charge and cause complicated thermo-mechanical behaviors of the composite structure. This study presents an analytical model, as validated by computational fluid dynamics (CFD) simulations, to study the thermal properties of composite hydrogen storage cylinder during fast filling process. A simple analytical formula for the gas temperature within cylinder and the temperature distribution in solid walls are obtained, which show intuitively the effects of different material and geometry parameters on thermal properties of the cylinder. Furthermore, a 3D finite element analysis (FEA) model, using the analytical results of temperature distribution, is proposed to investigate the coupled thermo-mechanical behaviors of the cylinder. FEA results reflect that the plastic behavior of aluminum liner effectively isolate the thermal stress, and helps to relieve the thermal effects on the whole cylinder in a large extent.

Introduction

The shortage of fossil fuels and the pollution caused by their usage has created a clear demand for alternative sources of clean and renewable energy. Hydrogen as a clean energy carrier termed as ‘green fuel’ and the ‘fuel of the future’, may serve as a potential energy storage system, which on combustion yields only water vapor contributing to near zero emission [1,2]. Despite numerous benefits of hydrogen, its storage and delivery has been a severe bottleneck and there have been considerable efforts in finding novel methods for developing new processes to increase the hydrogen storage capacity.

Currently, the composite pressure vessels develop rapidly in the field of hydrogen storage due to their advantages such as high strength/stiffness-to-weight ratios [3]. For example, the hydrogen fuel cell cars used in both 2008 Beijing Olympic Games and 2010 Shanghai World Exposition used composite high pressure storage vessel. To reach the aim of large-

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capacity hydrogen storage, the composite vessels are designed including an inner aluminum layer and several outer carbon fiber/epoxy composite wound layers. In general, the carbon fibers are wrapped around the pressure vessel following different orientations for different layers and in a common orientation within a layer. These layers are stacked in such a way to achieve high stiffness and strength [4].

However, the fast filling of hydrogen can lead to a significant temperature rise within the vessel due to the Joule Thomson effect and the released heat of gas compression [5]. The shorter the filling time should be the higher the maximum temperature in the cylinder climbs. The composite vessels are directly subjected to the cyclic loading of both high pressure and temperature, which can seriously influence mechanical properties of the carbon fiber/epoxy composites. Further, the complicated failure mechanisms and degradation mechanisms are distinct characteristic of composites although they exhibit high stiffness- and strength-density ratios [6]. So it is crucial to understand the coupled thermo-mechanical phenomena during a fast filling process to keep the composite structure within the safety margins.

So far, many numerical and experimental researches have been done on the thermal effects of fast filling. Data on fast filling experiments can be found in Liss and Richards [7], Wong and Gambone [8], Shen et al. [9], and Colom [10]. Yang [11] performed some thermodynamic analysis of hydrogen as ideal or non-ideal gas during the refueling process. Wang et al. [12], Kim et al. [13] and Galassi et al. [14] studied the temperature rise of fast filling using CFD-based simulation. Zheng et al. [15] conducted fast filling fatigue test to investigate the thermal effects and fatigue behavior of the composite vessel. Song et al. [16] investigated the thermo-mechanical properties of composite vessel under atmospheric fatigue cycling. However, the theoretical analysis of temperature development in hydrogen cylinder during fast filling is a challenging task and only a small amount of primary work has been published. In addition, the thermo-mechanical properties of composite cylinder during fast filling are rather complicated, and still in need of both numerical analysis and experimental investigations.

The aim of this work is to develop an analytical model, as validated by 2D CFD simulation, to study the thermal properties of the composite cylinder in fast filling. A simple expression of final gas temperature and temperature distribution in the two solid layers are established analytically in terms of material and geometry parameters of the cylinder. Furthermore, a three dimensional elasto-plastic finite element model is present to investigate the coupled thermo-mechanical behaviors of the cylinder during fast filling. The results in this paper are very useful for the design and optimization of the composite high-pressure hydrogen storage cylinder.

Heat conduction model for the composite cylinder

Theoretical analysis

The fast filling process can be theoretically modeled as two continuous processes: an adiabatic filling process, followed by a steady-state heat conduction process. A simple analytical result

$$T_{adiabatic} = \lambda t_o, \tag{1}$$

has been obtained to estimate the final gas temperature of adiabatic filling, whereλ is the ratio of specific heat under constant volume to that under pressure, based on the National Institute of Standards and Technology data, λ is assumed as 1.38 [17]. The analytical result agrees very well with the numerical simulation when the initial gas pressure is less than 2 MPa. The steady-state heat conduction process is the heat dissipation process of the high temperature hydrogen as a result of adiabatic filling, which leads to a lower gas temperature within cylinder and a gradient temperature distribution in the solid walls.

For simplicity, an axisymmetric model is adopted to obtain the analytical solution of the steady-state heat conduction process. As shown in Fig. 1(a) and (b), the composite cylinder is composed of three domains: the inner-most domain is the gas domain which is connected to the liner domain (aluminum alloy), and the outer domain is the carbon fiber/epoxy composite layers. The thickness of the liner and composite layer is h_l and h_c, respectively. Their corresponding thermal conductivities and specific heat capacities are k_l, k_c and c_l, c_c. The ambient temperature is t_o, and the initial and final gas temperature within cylinder is t_a ($t_a = \lambda t_o$) and t_g. The heat conduction equation is

$$\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial z^2} = 0 \tag{2}$$

where T is the temperature, and (r, z) are the cylindrical coordinates with the z-axis corresponding to the symmetric axis of the cylinder (Fig. 1b). The standard deviation of hydrogen temperature within the cylinder (excluding the jet path) is relatively small [18], which can be treated as homogeneous. Besides, the temperature distribution is uniform in z direction, such that heat transfer occurs mainly along radial direction. The heat conduction equation Eq. (2) can be further simplified as

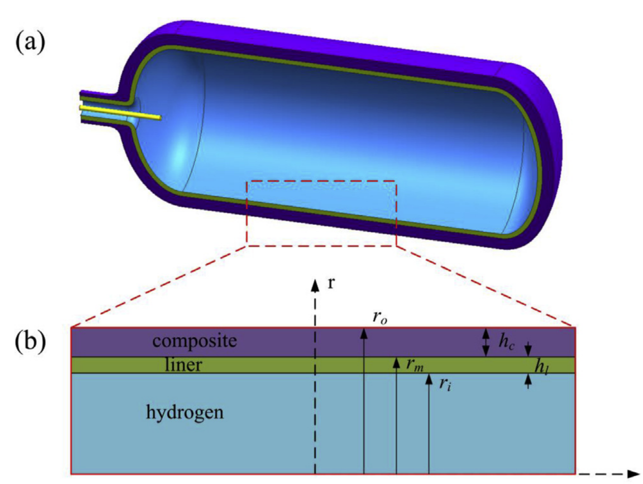

Fig. 1 – A schematic of the composite cylinder structural: (a) three-dimensional and (b) theoretical model.