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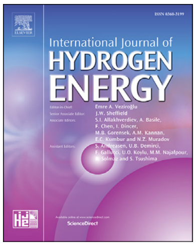

Supercritical cryo-compressed hydrogen storage for fuel cell electric buses

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ABSTRACT

Liquid hydrogen (LH_2) truck delivery and storage at dispensing sites is likely to play an important role in an emerging H_2 infrastructure. We analyzed the performance of single phase, supercritical, on-board cryo-compressed hydrogen storage (CcH_2) with commercially-available LH_2 pump enabled single-flow refueling for application to fuel cell electric buses (FCEB). We conducted finite-element stress analyses of Type 3 CcH_2 tanks using ABAQUS for carbon fiber requirement and Fe-Safe for fatigue life. The results from these analyses indicate that, from the standpoint of weight, volume and cost, 2-mm 316 stainless steel liner is preferred to aluminium 6061 alloy in meeting the required 15,000 charge-discharge cycles for 350–700 bar storage pressures. Compared to the Type 3, 350 bar, ambient-temperature H_2 storage systems in current demonstration FCEBs, 500-bar CcH_2 storage system is projected to achieve 91% improvement in gravimetric capacity, 175% improvement in volumetric capacity, 46% reduction in carbon fiber composite mass, and 21% lower system cost, while exceeding >7 day loss-free dormancy with initially 85%-full H_2 tank.

Introduction

City buses, waste-hauling, and parcel-delivery trucks may offer a suitable platform for facilitating market entry of transportation fuel cells and laying hydrogen infrastructure in advance of commercial readiness for light-duty vehicles (LDV). Among many favorable factors, the buses (and trucks) require a limited infrastructure investment compared to LDVs since they return to a central depot for refueling and parking at night. The acceptable costs for fuel cell systems (FCS) for buses are less stringent than $30/kW for LDVs. This wider latitude in cost translates to greater material and technology choices (e.g., Pt loading in cathode catalyst higher than 0.1 mg/cm^2) for enhanced durability. Also, the required FCS production volumes and initial investment are much lower for buses than for LDVs at 500,000 units/year [1].

The current generation of fuel cell electric buses (FCEB) being demonstrated store hydrogen as compressed gas at 350-bar in Type-3 tanks [1,2]. Typically, these FCEBs are equipped with 8 hydrogen cylinders that store a total of 40-kg H_2 to provide a driving range of ~500 km [3]. The metal cylinders are reinforced with carbon fiber (CF) composite that carries a majority of the pressure load and represents a significant fraction of the tank cost. As a reference, recent studies on

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Nomenclature

A	surface area
C	specific heat
h	enthalpy
k	rate constant
k	heat transfer coefficient
m	mass
$\dot{m}$	mass flow rate
P	pressure
$\dot{Q}$	heat transfer rate
t	time
T	temperature
u	internal energy
V	internal volume of tank
x	fraction of ortho hydrogen
ρ	density

Subscripts/Superscripts

a	ambient
e	electric (or equilibrium)
g	gas
in	inlet
l	liquid
o	o-H2
out	outlet
p	p-H2
r	leakage
s	saturation (or structure)

compressed hydrogen (cH_2) storage at 700-bar in Type-4 tanks (plastic liner) for LDVs estimate that the CF composite accounts for ~70% of the total projected cost of the on-board system [4–6] at high production volumes.

Hydrogen liquefaction at a central production site or at city gate and delivery in liquid H_2 (LH_2) trucks to dispensing stations is considered an important pathway during any transformation to large-scale hydrogen economy [7–10]. Gaseous H_2 (GH_2) delivery in tube trailers is viable only at small (<5%) market penetration and limited H_2 demand. Conversely, gaseous pipeline delivery and distribution is attractive only at large market penetration (>30%) [8,9]. In the intermediate stage of market penetration, dispensing stations will likely receive hydrogen by a combination of GH_2 delivery and LH_2 delivery. A recent California study [11] estimated this split as 25% GH_2 delivery and 75% LH_2 delivery changing to 85% liquid delivery and 15% on-site H_2 production by steam methane reforming (SMR) as the market matures. The study also projected that the initial costs for 400 kg/d H_2 fueling stations would be slightly lower for the pathway with LH_2 delivery than with GH_2 delivery and significantly lower than for on-site SMR.

On-site LH_2 storage is particularly favorable for large refueling stations such as bus depots [7]. Currently, the refueling stations with LH_2 storage incur relatively high operating costs and achieve low efficiency as they vaporize the liquid and compress GH_2 to high pressures needed for on-board cH_2 storage at 350 or 700 bar. Recently, a cryogenic LH_2 pump has become available that is capable of achieving outlet pressure >850 bar, flow rate >100 kg/h, and H_2 density >80 g/L [12]. This pump can replace the high-pressure GH_2 compressor to realize high efficiency and low operating costs while eliminating the refrigeration requirement for 700-bar cH_2 storage. Alternatively, even higher efficiency and lower operating costs can be realized if the pump is used to enable single-flow refueling of a cryo-compressed hydrogen (CcH_2) storage system on-board FCEB or LDV. The purpose of this work is to analyze the performance and attributes of this storage method.

Hydrogen storage at cryogenic temperatures in insulated pressure vessels was developed and demonstrated by Aceves and colleagues [12–20] to overcome the inherent dormancy issues while retaining or augmenting advantages associated with storing LH_2 in low-pressure vessels. They have built several generations of CcH_2 tanks for service at pressures from 274 to 700 bar, with recent focus on demonstrating volumetric efficiency approaching 80% [12]. An automotive manufacturer has further developed and showcased the CcH_2 storage technology in fuel cell demonstration vehicles [21,22]. An energy company has built a public fueling station to dispense liquid H_2 to these vehicles [23]. We have published several papers on the dynamics of CcH_2 storage with single and double-flow refueling, enhancement of loss-free dormancy with para-to-ortho isomer conversion, and well-to-wheel energy efficiency and cost [24–26]. The focus of this work is on analyzing the: 1) achievable performance of single-phase, supercritical CcH_2 storage with LH_2 pump enabled single-flow refueling, 2) issues of metal liner fatigue in Type 3 vessels for service at cryogenic temperatures, and 3) loss-free dormancy on FCEB and LDV duty cycles.

Modeling approach

Thermodynamics and kinetics of cryo-compressed hydrogen storage

Previous work has shown that the important aspects of cryo-compressed hydrogen storage can be captured with a simple model that accounts for thermodynamics, heat transfer, and kinetics of isomer conversion. Assuming that the pressure and temperature in the tank are uniform, H_2 is present as a single-phase (gas or supercritical fluid) mixture of ortho (o) and para (p) isomers [26–28], and the kinetic energy of H_2 flowing in and out of the tank is negligible, we write the following equations for H_2 mass and energy balance [24,25].

$$\frac{dm_{H_2}}{dt} = \dot{m}^{in}_{H_2} - \dot{m}^{out}_{H_2} \tag{1}$$

$$\frac{d}{dt}\left[m_s u_s + m_{H_2} u_{H_2}\right] = \dot{m}^{in}_{H_2} h_{in} - \dot{m}^{out}_{H_2} h_{H_2} + \dot{Q}^{r}_{in} + \dot{Q}^{e}_{in} \tag{2}$$

where

$$m_{H_2} u_{H_2} = m_{H_2}\left(h_{H_2} - P/\rho_{H_2}\right), \tag{3}$$

$$h_{H_2} = x h^{o}_{H_2} + (1 - x) h^{p}_{H_2}, \tag{4}$$

$$\rho_{H_2} = \left(\frac{x}{\rho^{o}_{H_2}} + \frac{1 - x}{\rho^{p}_{H_2}}\right)^{-1}, \tag{5}$$