On-Board Cold Thermal Energy Storage System for Hydrogen Fueling Process

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Abstract

The hydrogen storage pressure in fuel cell vehicles has been increased from 35 MPa to 70 MPa in order to accommodate longer driving range. On the downside, such pressure increase results in significant temperature rise inside the hydrogen tank during fast filling at a fueling station, which may pose safety issues. Installation of a chiller often mitigates this concern because it cools the hydrogen gas before its deposition into the tank. To address both the energy efficiency improvement and safety concerns, this paper proposed an on-board cold thermal energy storage (CTES) system, cooled by expanded hydrogen. During the driving cycle, the proposed system uses an expander, instead of a pressure regulator, to generate additional power and cold hydrogen gas. Moreover, CTES is equipped with phase change materials (PCM) to recover the cold energy of the expanded hydrogen gas, which is later used in the next filling to cool the high-pressure hydrogen gas from the fueling station. A few years ago, the typical hydrogen storage pressure in fuel cell vehicles was 35 MPa; such pressure produced a very low volumetric energy density to accommodate long-range driving that would require 70 MPa. Recently, on-board hydrogen storage, mainly in high pressure of 70 MPa, has been widely adopted. This increase of pressure, however, leads to a significant rise in the temperature of the vehicle tank during fast filling at a fueling station due to heat of compression and Joule–Thomson expansion. Pre-cooling hydrogen with a chiller before refueling mitigates the temperature rise to meet the maximum allowable tank temperature that conforms to international standards and regulations such as the Society of Automotive Engineers (SAE) protocol and the International Organization for Standardization (ISO) safety code (i.e., 85 °C) . Such temperature rise during the filling process also reduces the total amount of gas stored inside the tank. In a series of experiments, Kim et al. quantified temperature change on the cylinder of the tank using computational fluid dynamics (CFD) analysis. Miguel et al. evaluated the effect of the filling rate on the gas temperature increase and investigated the thermal response of the metallic bosses and the external surface of the tanks under different cycling conditions. Monde et al. validated their model via experiments and mentioned parameters affecting the filling process to determine the filling time or precooled temperature. In several refueling experiments, Zheng et al. investigated the temperature rise during refueling and validated a CFD model; results showed that an increase in initial pressure and a decrease in ambient temperature lead to an approximately linear decrease in final gas temperature. Moreover, Miguel et al. investigated the influence of initial tank temperature on refueling of two different on-board hydrogen tanks, four different fuel delivery temperatures (from ambient temperature refueling to a pre-cooled hydrogen at −40 °C), several filling rates, and initial pressures. Xiao et al. proposed a new analytical solution of pre-cooling hydrogen temperature from a simplified lumped parameter model, and investigated the effects of initial temperature, initial pressure, and the filling time on the inflow hydrogen temperature. Installation of a pre-cooling system in a hydrogen refueling station invites cooling demand, thus significantly increasing the initial cost, as well as the running costs of the station, in terms of energy consumption. Elgowainy et al. conducted a techno-economic and thermodynamic analysis of hydrogen precooling units for T40 stations, and they examined the key factors that contribute to the cost and energy use of hydrogen precooling. Cebolla et al. executed filling experiments with different inlet gas temperatures and mass flow rates and stated that the lowest precooling temperature (−40 °C) is not always required in order to meet the user's requirements. To reduce the cooling demand at the fueling station, Melideo and Baraldi proposed a convenient filling strategy, with an almost linear pressure rise and pre-cooling in the second half of the process, which achieved a 60% reduction of cooling energy demand compared to the entire filling pre-cooling by the CFD analysis.

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On a parallel note, the storage system consumes more energy to compress hydrogen at higher pressures of 70 MPa. Because the energy consumed during filling cannot be recovered, energy efficiency at higher pressure storage decreases. According to the well-to-wheel analysis of fuel cell vehicles by Campanari et al., the conversion efficiency of energy consumed at a refilling station (energy consumption for each kWh of energy given at the vehicle wheels) to compress hydrogen to 70 MPa from the pipeline (at 6 MPa) is 65%. In this study, a recovery system for hydrogen pressure energy in a fuel cell vehicle is proposed. During pressure regulation in the vehicle, an expander is used to recover the pressure energy and produce additional power. In addition, the cold energy of expanded hydrogen is stored in an on-board cold thermal energy storage (CTES) system. It is later used to cool the high-pressure hydrogen gas before filling. Thus, it reduces (or eliminates) energy consumption by the chiller at the fueling station. A simple thermodynamic analysis is used to investigate the feasibility of the new system. The aim of this study is to show the potential energy-saving methods for fuel cell vehicles and measures of effectiveness, which have so far been difficult to find in the available literature.

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