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Two-tier pressure consolidation operation method for hydrogen refueling station cost reduction

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ABSTRACT

An operation strategy known as two-tier "pressure consolidation" of delivered tube-trailers (or equivalent supply storage) has been developed to maximize the throughput at gaseous hydrogen refueling stations (HRSs) for fuel cell electric vehicles (FCEVs). The high capital costs of HRSs and the consequent high investment risk are deterring growth of the infrastructure needed to promote the deployment of FCEVs. Stations supplied by gaseous hydrogen will be necessary for FCEV deployment in both the near and long term. The two-tier pressure consolidation method enhances gaseous HRSs in the following ways: (1) reduces the capital cost compared with conventional stations, as well as those operating according to the original pressure consolidation approach described by Elgowainy et al. (2014) [1], (2) minimizes pressure cycling of HRS supply storage relative to the original pressure consolidation approach; and (3) increases use of the station's supply storage (or delivered tube-trailers) while maintaining higher state-of-charge vehicle fills.

Introduction

Hydrogen fuel cell electric vehicles (FCEVs) — vehicles that offer virtually zero emissions — are being promoted worldwide, including in Germany [2], Japan [3], the United Kingdom [4], and the United States [5]. In the United States, FCEVs are currently deployed primarily in California, with approximately $20 million in annual funding from the California Energy Commission to support the deployment of up to 100 hydrogen refueling stations (HRSs) by 2022 [6]. Currently, there are about 45 retail HRSs open or under construction in California and three FCEV models — from Hyundai (Tucson), Toyota (Mirai), and Honda (Clarity) — available for lease and purchase [7]. The lack of a widespread refueling network is the main barrier to early adoption of FCEVs [8,9]. The high capital cost of HRSs and the consequent high investment risks are the main culprits behind the lack of progress in deploying the large-scale hydrogen refueling infrastructure needed to promote the deployment of FCEVs in various markets [10]. The investment risk is exacerbated by under-utilization of refueling station capital in early markets [10]. Growth in the market penetration of FCEVs will require a reduction in the costs of both the vehicles and the hydrogen fuel to make the cost of driving an FCEV competitive with the costs for alternatives (e.g., internal combustion engine vehicles, hybrid electric vehicles, and plug-in battery electric vehicles). In this paper, we present an approach to reducing the cost of hydrogen by lowering the capital cost of HRSs.

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The cost of hydrogen sold at an HRS is based on the following costs: (1) hydrogen production, (2) hydrogen delivery to HRS, and (3) hydrogen fueling at the HRS [10]. Currently, hydrogen delivery and dispensing costs account for over three-fourths of the total hydrogen cost to customers; fueling alone accounts for approximately one-half of the total hydrogen cost, mainly because of the currently high capital and operational costs of HRSs [10]. Reddi et al. (2017) provided a detailed evaluation of the parameters influencing hydrogen refueling costs, along with estimates of these costs in the short term and long term [10].

HRS costs depend on the station's design and configuration, which depend on the physical state in which hydrogen is supplied to the station (i.e., as a compressed gas or a liquid [10,11]. Gaseous hydrogen can be supplied to the refueling station by an onsite production unit (e.g., natural gas reformer or electrolyzer) or by pipeline or tube-trailer. In the near term, the potential of building HRSs with onsite production is limited because onsite production units require additional land area and power. In the near term, tube-trailer delivery to HRSs requires less station land area and consumes less energy compared to liquid hydrogen delivery, and is less capital-intensive than pipeline delivery [10,12]. In the long term, pipeline delivery is likely to become viable economically when the demand for hydrogen is substantial and predictable. Today, hydrogen pipelines are built primarily to supply the petrochemical industry, where the demand for hydrogen is thousands of tonnes per day. Currently, most of the hydrogen refueling stations in California are supplied by tube-trailers.

In this paper, we propose an operating method that involves two-tier pressure consolidation to reduce the cost of hydrogen refueling stations supplied by gaseous hydrogen. The proposed method reduces the compressor size and buffer storage capacity required to meet a given station daily demand, thus reducing the overall station cost. This method builds on the pressure consolidation method previously proposed by Elgowainy and Reddi (2014), which was recently patented in the United States [1,13]. In the next section the research background and the newly proposed pressure consolidation refueling method are presented, followed by the simulation results of HRS operation. We note that the proposed method is equally applicable to stations with (1) vessels that are delivered by tube-trailers, kept onsite, and replaced periodically when they empty (i.e., “drop and swap”), and (2) stationary onsite storage that is filled by tube-trailers or other methods of gaseous hydrogen supply (e.g., onsite hydrogen generation or pipelines). The configuration of stations supplied by the former approach is outlined in Fig. 1.

Research

Background: refueling station operation

Fig. 1 shows the components of an HRS supplied by a tube-trailer. If the station is instead supplied by gaseous hydrogen from other sources (e.g., onsite production or pipeline), the tube-trailer would be replaced with stationary storage vessels. The tube-trailer typically has a maximum loading pressure between 200 and 500 bar (at 15 °C) and a minimum (empty) pressure of about 20–50 bar [14]. The refueling station's compressor draws hydrogen from the tube-trailer to fuel FCEVs until the pressure in the tube-trailer drops to its practical minimum pressure, assumed here to be 20 bar. When the minimum operation pressure is reached, the tube-trailer is swapped with another fully loaded tube-trailer or replenished from an alternative hydrogen supply source.

When a consumer activates the dispenser for vehicle refueling, the dispenser directs the flow of hydrogen from the high-pressure buffer storage via the chiller into the vehicle's onboard storage (tank). The chiller precools the hydrogen flow to -40^{O}C, while the dispenser measures and controls the flow according to a standard fueling protocol [15,16]. The compressor increases the hydrogen pressure from the tube-trailer (or stationary storage) to about 950 bar in the high-pressure buffer storage vessels that cascade the fueling into the vehicle's onboard tank. In a conventional station, the compressor remains idle when the high-pressure buffer is at maximum operating capacity and operates only to replenish the high-pressure buffer when it is not at maximum capacity. Fig. 1 also shows the typical cost contribution of each refueling component toward the refueling cost of hydrogen. The compressor contributes to approximately half of the hydrogen refueling cost [10]. Thus, by reducing the size and cost of the compressor, the cost associated with hydrogen refueling can be reduced considerably. Previous work simulated the operation of HRSs to optimize the compression and buffer storage [1,17–19] and vehicle fill time [20], but did not consider pressure consolidation of the supply storage proposed here.

Background: compressor operation

As shown in Fig. 2, throughput of a compressor is determined by the displacement volume in the compressor's cavity (V), the frequency of compression (N) in cycles per unit time, and the density of the gas supplying the compressor (ρ). Since the density of the gas increases with its pressure at any given temperature, the compressor flow rate (throughput) is proportional to the pressure of the gas at the compressor suction (or inlet), as shown in Fig. 2. Thus, a higher suction pressure leads to a higher compressor flow rate. Since the flow rate of the compressor varies with suction pressure, the compressor is typically rated at the lowest suction pressure it is likely to experience at fueling stations, which is the minimum supply storage pressure, assumed here to be 20 bar.

Fig. 3 shows an empirical flow curve supplied by a leading compressor manufacturer in the United States (PDC Machines Inc.) for a compressor with 8 kg/hr throughput at a suction pressure of 20 bar. This compressor can serve a 200-kg/day refueling station capacity with appropriately sized high-pressure buffer storage capacity. However, as shown in Fig. 3, if the suction pressure of the compressor is maintained at a higher level, the compressor can achieve a higher throughput and therefore serve a much larger station demand [14]. The same compressor can be used to address daily refueling demands of 400, 600, or 800 kg/day at minimum compressor suction pressures of 75, 115, or 155 bar, respectively. For a typical station supplied by a tube-trailer, designing the compressor for these minimum supply pressures of 155, 115, or 75 bar is not practical, since this would