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Techno-economic and thermodynamic analysis of pre-cooling systems at gaseous hydrogen refueling stations

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ABSTRACT

We conducted a techno-economic and thermodynamic analysis of precooling units (PCUs) at hydrogen refueling stations and developed a cost-minimizing design algorithm for the PCU observing the SAE J2601 refueling protocol for T40 stations (requiring −40 °C precooling temperature). In so doing, we identified major factors that affect PCU cost and energy use. The hydrogen precooling energy intensity depends strongly on the station utilization rate, but approaches 0.3 $kWh_e/kg\text{-}H_2$ at full utilization. In early fuel cell electric vehicle markets where utilization of the refueling capacity is low, the overhead cooling load (to keep the heat exchanger cold at −40 °C) results in significantly high PCU energy intensity because only a small amount of hydrogen is being dispensed. We developed a parameterized pre-cooling energy intensity prediction formula as a function of the ambient temperature and station utilization rate. We also found that the Joule-Thomson effect of the flow control device introduces a significant increase in temperature upstream of the PCU's heat exchanger (HX), which impacts the PCU design capacity. An optimal PCU (per dispenser, at 35 °C HX inlet temperature) consists of a 13-kW refrigerator and a HX with 1400 kg of thermal mass (aluminum), which currently costs $70,000 (uninstalled). The total (installed) capital and operation cost of PCU at a fully utilized hydrogen refueling station adds $0.50/ $kg\text{-}H_2$.

Introduction

Zero-emission vehicles (ZEVs) such as hydrogen fuel cell electric vehicles (HFCEVs) can eliminate petroleum use and reduce air pollutant emissions from the transportation sector. They also have lower well-to-wheels (WTW) greenhouse gas emissions compared to gasoline and diesel internal combustion engine vehicles [1,2]. Compared to other ZEVs such as battery electric vehicles (BEVs), HFCEVs provide a much longer driving range and shorter fueling time; these two factors influence consumer experience and thus are critical to the successful deployment of commercial HFCEVs. However, a

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lack of adequate hydrogen delivery infrastructure is a major barrier to the large-scale deployment of HFCEVs.

The cost of hydrogen in early HFCEV markets is dominated by the cost of refueling stations, mainly due to the high cost of refueling equipment, small station capacities, lack of economies of scale, and low utilization[1] of the installed refueling capacity. The current hydrogen refueling station levelized cost, for a 200-kg/day dispensing capacity, is in the range of \$6–\$9/kg-H_2. After adding the cost of hydrogen production, packaging, and transportation to the station's levelized cost, the current cost of hydrogen at dispensers for HFCEVs in California is in the range of \$13–\$15/kg-H_2 [3].

At present, with existing modes of hydrogen transportation and distribution, hydrogen refueling stations (HRSs) accounts for about 50% of the fuel cost at the pump [4–8]. A typical HRS is comprised of a compressor, a hydrogen storage unit, a dispenser, a precooling unit (PCU), and control/safety equipment [6,9–12]. The precooling unit cost constitutes about 10% of the station's total equipment cost [3], and a deeper understanding of its cost component is necessary to achieve the maximum possible HRS cost reduction. The existing body of systems analysis literature on HRSs provides detailed information on compressor and storage systems, as well as their operating strategies and interactions [6,10]. In contrast, relatively limited information is available on PCU designs, costs, energy use, or performance. A variety of international experts and stakeholders acknowledge that more research and analysis is needed to understand precooling system costs and design optimization [13]. Precooling of the hydrogen fuel before it is dispensed into the vehicle's tank is critical to prevent the tank from overheating. The SAE J2601 fueling protocol establishes fueling process limits to ensure safe and rapid filling of HFCEVs [14].

The SAE J2601 fueling protocol establishes a hydrogen precooling temperature range for each hydrogen refueling station type; for example, a T40 station is required to precool the hydrogen to between −33 and −40 °C before dispensing it to the FCEV. Situated between the high-pressure buffer storage unit and the dispenser, the PCU precools the gaseous hydrogen to a temperature of at least −33 °C within 30 s of the start of fueling. It then maintains a temperature in that prescribed range for the entire duration of the fueling event. The speed at which FCEVs can be refueled is directly related to the hydrogen precooling temperature, the ambient temperature, and the initial onboard tank pressure [15] among other factors. The higher the ambient temperature is, the longer it will take to fill the tank, and vice versa. However, among these three key factors, precooling has the most significant impact on the refueling time. Because the refueling time is one of the critical parameters that affects HFCEV fueling experience, the precooling system should be designed to deliver the required fueling rate and capacity under extreme conditions, and at the lowest cost possible. This in turn calls for a techno-economic and thermodynamic analysis approach of the PCUs at HRSs.

This paper identifies and examines key factors that contribute to the cost and energy use of PCUs at HRSs. We also quantify the impacts of other major precooling parameters, including the Joule-Thomson (J-T) effect, using theoretical analysis and real-world validation. We also assess the trade-offs involved in different precooling system designs and evaluate the potential for reductions in cost and energy consumption while maintaining refueling performance. Along with the data and formulas, the PCU design and optimization algorithm developed in this study can provide useful insights to HRS researchers, designers, and operators.

In the following sections, we first describe the HRS precooling system, provide a review of the relevant literature, and discuss the precooling system design options, performance, and operation strategies and characteristics (Section Precooling unit (PCU) for HRS). In Section Material and methods, we provide details on the precooling energy calculations and the cost of components. We also explain our PCU system modeling methods and assumptions, and our approach to optimize the PCU size by minimizing the total precooling cost. Then we introduce the factors that affect the sizing of PCU components and the simulation parameters in Section Simulation setup. We then present and discuss the results in Section Results, including the optimum size of precooling system components, the precooling cost and energy consumption estimates, and the impact of key design factors on the precooling system cost and performance. Finally, we describe our conclusions in Section Conclusions.

Precooling unit (PCU) for HRS

A typical PCU in an HRS utilizes a thermodynamic refrigeration cycle; it circulates a refrigerant (e.g., R404A) through a two-stage compressor, condenser, thermostatic expansion valve, and evaporator heat exchanger (Fig. 1). This refrigeration cycle involves a refrigerant sub-cooling to maximize the refrigeration effect at the evaporator by circulating a portion of the refrigerant exiting the condenser through the expansion valve, the sub-cooler HX, and the compressor's second stage. The dispensed hydrogen is precooled by releasing energy to the low-temperature refrigerant through the evaporator HX. The evaporator heat exchanger can be designed with a large thermal mass (mainly to act as a buffer and thereby reduce the required refrigeration capacity), or it can have a compact design for packaging purposes. Table 1 provides a qualitative comparison between large thermal mass and compact HXs. Each has its own advantages and disadvantages. Because of the buffering effect the large thermal mass provides during refueling, the temperature of the HX may rise with each refueling, which necessitates additional cooling during idle times. Regardless of HX design, heat gain from the ambient atmosphere due to imperfect insulation causes the HX's temperature to increase over time. Therefore, intermittent overhead cooling is necessary to keep the HX at −40 °C in anticipation of refueling demand that may arise at any time. In this case, the refrigeration unit operates when the temperature of the HX exceeds a predetermined threshold, which varies with HX size and type.

Two major factors affect refrigeration performance and the sizing of the PCU: the J-T expansion process (or throttling effect) at the variable area control device (VACD) upstream of

[1] Station utilization is defined as the ratio between the amount of daily hydrogen dispensed to the daily design capacity of the station.