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Effect of cascade storage system topology on the cooling energy consumption in fueling stations for hydrogen vehicles

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ABSTRACT

One of the main obstacles of the diffusion of fuel cell electric vehicles (FCEV) is the refueling system. The new stations follow the refueling protocol from the Society of Automotive Engineers where the way to reach the target pressure is not explained. This work analyzes the thermodynamics of a hydrogen fueling station in order to study the effects of the cascade storage system topology on the energy consumption for the cooling facility. It is found that the energy consumption for cooling increases, expanding the total volume of the cascade storage system. Comparing the optimal and the worst volume configurations of the cascade storage tanks at different ambient temperatures, the energy saving is approximately 12% when the average ambient temperature is 20 °C and around 20% when the average ambient temperature is 30 °C. The energy consumption for cooling is significantly influenced by the topology of the cascade storage system and it is particularly relevant in the case of low daily-dispensed amount of hydrogen.

Introduction

Hydrogen produced from renewable energy sources (RES) is a potential substitute for common fossil energy carriers. In recent years, numerous installations of renewable power production have been built, in particular photovoltaic and wind turbines facilities. Since solar and wind energy productions are fluctuating, they cannot provide reliable base load power. For that reason, a large-scale energy storage is required to compensate the seasonal imbalances. Hydrogen from renewable resources could be used as a fuel in the transport sector or even as feedstock in the industry. In a case study conducted by Robinius et al. [1] for Germany found out that an increase of 75% of hydrogen vehicles could be supplied by renewably produced hydrogen in 2050. The use of hydrogen as a carbon-free road transport fuel offers ecological as well as economic benefits. Like battery electric cars, fuel cell cars run emission-free and can be refueled as quickly as gasoline-powered cars. The main obstacle of the diffusion of the FCVs (Fuel Cell Vehicles) is the refueling system. The construction of CHG (Compressed Hydrogen Gas) fueling stations costs up

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to $2 million [2], which is the main reason why companies have been reluctant to invest until more fuel cell cars are on the road. Automobile manufacturers on the other hand do not produce cars that consumers are not able to fuel. Therefore, a basic coverage of fueling stations is mandatory to offer an incentive for potential customers. The number of hydrogen refueling stations is increasing worldwide with most of them being built by universities, research centers, governments and industry shareholders [3]. Fueling stations all over the world follow the standardized protocol from the Society of Automotive Engineers, SAE J2601 [4]. In the protocol the outlet temperature, the average pressure ramp rate and the final pressure at which the refueling should end are declared for different initial conditions of the system. The way to reach the target pressure under known initial conditions is not specified. Therefore, the hydrogen refueling stations are designed differently. Although the design is different, there are some similarities like the cascade storage system, the compressor used to refill the cascade and the heat exchanger to cool the hydrogen before the dispenser. Hydrogen Refueling stations have to meet several requirements, among others, not to reach a temperature higher than 85 °C in the gas inside the tank during the refueling [4]. This temperature limit of 85 °C is set for two reasons, first to protect the tank materials from thermal degradation, and second to be able to fill the tank (100% state of charge) without exceeding the maximum working pressure (125% of the nominal working pressure) [5].

Reports from hydrogen refueling stations indicated that cooling energy consumption exceeded 10 kWh/kg_{H_2} [6]. This amount of energy consumption not only has an impact 1$/$kg_{H_2}$ [6] on the operating cost, but also increases the green house gas emissions associated with hydrogen dispensing. The amount of electrical energy required to pre-cool the hydrogen should be around 10% of a fueling station's overall energy consumption in condition of full operation. On the contrary, at present stage the stations spend 80% of the overall energy on cooling [6]. This is because of the low daily-dispensed amount of hydrogen. Therefore, it is important to analyze the cooling energy consumption for different initial conditions of the refueling system, such as the ambient temperature and the topology of the cascade storage system, and to reduce the costs of hydrogen refueling stations. A comprehensive thermodynamic model of hydrogen refueling stations, which regards the impact of the cascade storage system topology and of the initial temperature on the cooling energy consumption, is not known from the literature.

Various research studies are concerned with CHG (Compressed Hydrogen Gas) refueling stations. Most of them include analytical thermodynamic models used to study temperature, pressure and mass flow rate behavior inside the on-board vehicle tank during the fast filling process [7–11]. Xiao et al. [12] developed a thermodynamic model of the fast filling process to estimate the required pre-cooling temperature in order to avoid a temperature higher than 85 °C inside the vehicle tank during the filling process [4]. Striednig et al. [13] presented a thermodynamic model of a CHG refueling station considering not only the vehicle tank but also the reservoirs tanks. More elaborated thermodynamic models are used to optimize the station storage system: Elgowainy et al. [14] optimized the compression system considering a tube trailer as a way to reduce the compression and capital costs; Rothuizen et al. [15] analyzed the energy consumption to cool the hydrogen during the filling process, comparing a cascade storage system and a buffer storage system concluding that with cascade storage system of three tanks it can be saved 12% of energy for cooling. Farzaneh-Gord et al. [16] have done a research in the field of entropy generation and entropy consumption, comparing a buffer storage system with a cascade storage system. They found out that using a buffer storage system leads to a 55% higher entropy generation than using a cascade storage system. Hosseini [17] performed a parametric study to investigate the effect of initial conditions on the exergy efficiency of filling processes. They concluded that the exergy efficiency is higher when the tank is refilled with a higher initial pressure. Furthermore, in their study they didn't consider the cascade storage system. Rothuizen et al. [18] analyzed power consumption from the compressor of a refueling station as a function of number of tanks, volume of the tanks, and the pressure in the tanks without considering the effect of ambient temperature. They found out that the energy consumption decreases with the number of tanks approaching an exponential function. Their study is focused on number of tanks optimization and not on storage tanks size optimization. Furthermore, they analyzed the overall energy consumption without showing the amount of energy used to pre cool the hydrogen before the dispenser that at this stage of CHG fuelling station could help to have lower operating costs saving energy and consequently improve CHG fuelling stations number of installations.

The goal of the present work is to select the optimal volume configuration of the cascade storage system at different ambient temperatures in terms of cooling energy consumption. In detail, a thermodynamic analysis is performed considering a cascade storage system comprising three storage tanks. Different combinations of tank sizes and different initial ambient temperatures are analyzed. In the thermodynamic model used for simulation of the refueling system the heat losses from the tanks to the surrounding are neglected. Furthermore, hydrogen gas is considered to be a real gas.

Modeling and method

The following section explains the method used to model a hydrogen refueling station, including a description of the necessary theoretical background.

Schematic diagram of CHG fueling station

A CHG refueling station can be divided into five components: compressor, priority panel, reservoirs tanks, dispenser, and on-board cylinder. The compressor is used to refill the tanks of the cascade storage system when the pressure is decreased to a certain limit and the priority panel manages the refilling process. The storage tanks are filled one after the other. Firstly, high pressure storage tanks, then medium pressure storage tanks and finally low pressure storage tanks are filled by the compressor. The cascade storage system, used to fill the on-board cylinder, is divided into low, medium, and high pressures. During fast filling, the on-board cylinder is at first