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The effect of environmental conditions on the operation of a hydrogen refuelling station

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ABSTRACT

In this study, the effect of environmental conditions on plant operation was investigated for hydrogen refuelling stations with an external storage facility. Hydrogen storage pressure with respect to tank surface temperatures have been measured and used to create empirical equations for each tank showing the effect of surface temperature on the tank pressure. A physical model of the hydrogen storage tanks has been created in DesignBuilder (EnergyPlus) to simulate the surface temperature of tanks throughout the course of a year with respect to location, site orientation, tank size and surface colour, shading and operating pressure. Finally, the effect that environmental conditions may have on a plant operation is assessed through the prediction of pressure dependent events, namely the frequency of alarms and pressure relief occurrences and hours of plant downtime over the course of a year. The modelling results indicate that location, tank size, surface colour and sunshade can have substantial impacts on the plant operation, whereas the influence of site orientation is less significant. Frequency of pressure dependant events increase as the tank size decreases due to more significant heat gain observed with higher surface-to-volume ratios. Simulation results also prove that the provision of a sunshade or white paint colour could avoid/minimise the interference of ambient conditions in plant operation in cold and mild climates. However, they are not sufficient enough to mitigate against solar gain effect in warmer climates. Although reducing the maximum operating pressure would also help reduce the number of solar gain pressure events, it would also result in increased cushion level and hence reduced plant performance. The optimum design and operating strategy should be chosen for each individual station considering the daily and annual temperature profiles of the location.

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Introduction

Hydrogen is receiving much attention worldwide as a promising energy carrier and storage medium which can be used together with renewable energy resources to overcome the economic and environmental concerns over the excessive utilization of fossil fuels [1–4]. Hydrogen is one of the most abundant elements in the world and can be produced from a variety of resources which makes it a very attractive energy carrier for a sustainable energy future. It is expected that it will play a key role especially in decarbonisation of the transport sector and elimination of the tailpipe emissions from vehicles [5,6]. The world's largest automakers including Honda, Toyota, Renault-Nissan, Hyundai-Kia, Ford, Daimler and General Motors signed a Letter of Understanding on the development and market introduction of fuel cell vehicles in 2009 [7]. Hyundai has already introduced the first production model hydrogen fuel cell vehicle for sale [8]. Toyota and Honda announced their plans to launch a production fuel cell vehicle in late 2015 and 2016 respectively [9,10]. Ford, Daimler and Nissan under the Alliance with Renault have declared that they will collaborate to develop a common fuel cell system and launch affordable mass-market fuel cell cars by 2017 [11].

In order for a successful hydrogen delivery infrastructure to be realised, each station should provide an equivalent refuelling capability as that of conventional refuelling stations, especially in terms of station accessibility, refilling time e.g., dispensing 5 kg hydrogen in 3 min, and utilization of station and on-board energy storage capacities [12]. In more than 80% of installations hydrogen is stored under high pressure, primarily because of ease of use [13–15]. In order to meet the hydrogen demand for vehicle applications, the stations should be capable of delivering hydrogen at 350 bar or 700 bar, with 700 bar being likely to become the more common standard [16,17].

As the refuelling time is significant from the public acceptance point of view, several researchers have investigated the consequences of filling rate through the thermodynamic and heat transfer analyses from the perspective of the on-board hydrogen vessel [17–29]. The effect of filling speed on the temperature rise and distribution within the vehicle tank has been studied experimentally [22,27–29] and using Computational Fluid Dynamics (CFD) tools in order to investigate the optimum strategies for the refuelling procedure. A significant temperature increase (of the order of 70 °C or more) in the vehicle vessel was reported during the fast refuelling process as a result of the reverse Joule-Thomson effect [27]. This temperature increase reduces the density of hydrogen in the vessel preventing the operator from dispensing up to the rated mass of hydrogen under ambient conditions [13]. The simulations also showed decreased on-board storage capacities with rising ambient temperatures [21,24]. Additionally, cylinders with different diameters ratios, inlet diameters and material combinations have been examined to determine their influence on the vessel temperature distribution [20,25]. Finally, optimized control protocols and algorithms were proposed to achieve fast and safe filling processes while maximising the amount of hydrogen stored on-board [16,26].

Unlike studies focussing on the on-board hydrogen storage to meet performance targets, Farzaneh-Gord et al. [13] investigated the effects of station storage type and conditions on the refuelling station performance through the comparison of buffer storage and cascade storage systems using numerical estimations based on thermodynamics and mass conservation. The refuelling time required to achieve 350 bar on-board hydrogen pressure from a buffer storage system with 370 bar pressure was estimated to be around 66% less than that of the cascade system consisting of low, medium and high pressure tanks at 110 bar, 210 bar and 370 bar respectively. However, the entropy generation was 55% higher with the buffer storage system directly reflecting in the amount of compressor input work. It was concluded that cascade storage systems is more promising than a single high pressure vessel for hydrogen refuelling stations if the filling time is reduced by proper sizing of the piping system.

Similarly, Rothuizen et al. [30] studied the thermodynamics and design of hydrogen refuelling stations through a dynamic model to compare the refuelling process at 700 bar from a single tank at 900 bar and a multi-step storage system consisting of three tanks at 450 bar, 650 bar and 910 bar. The proposed cascade filling process reduced the compressor power consumption by 17%, cooling requirement during refuelling by 12% and time required for a whole cycle (refuelling a vehicle to 700 bar pressure and then refilling the station tanks) by 5% at the refuelling station compared to a single step refuelling process from a 900 bar pressure tank. It was also suggested that the hydrogen cushion level required to maintain the pressure in the storage tanks, but not used for refuelling, can also be decreased by using a multi-step refuelling procedure. The total mass required to be stored at the station to dispense 7 kg hydrogen with 700 bar final pressure to the vehicle was estimated to be 138.85 kg in a 900 bar tank and 112.3 kg distributed across the three tanks at 450 bar, 650 bar and 910 bar pressures. However, it must be noted that the model used in this study has not yet been validated with real data.

A review of research to date suggests that an important aspect of refuelling station performance which appears to be have been neglected is the effect of environmental conditions on the operation of a hydrogen refuelling station. This study has investigated the degree to which plant operation is sensitive to ambient conditions and in particular how these changing conditions impact on pressure dependant events affecting plant availability, i.e. high pressure alarms and/or activation of pressure relief valves. Change in tank surface temperature and resultant pressure fluctuation were measured experimentally using the external hydrogen storage facility available at Nottingham hydrogen refuelling station. The sensitivity of plant operation to environmental conditions were predicted over the course of a year with respect to location, site orientation, tank size and surface properties, shading availability and operating pressure using the DesignBuilder (EnergyPlus) simulations.