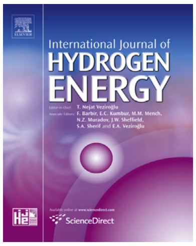
Available online at www.sciencedirect.com
ScienceDirect
journal homepage: www.elsevier.com/locate/he



The effect of defueling rate on the temperature evolution of on-board hydrogen tanks

N. de Miguel*, B. Acosta, P. Moretto, R. Ortiz Cebolla

Institute for Energy and Transport, Joint Research Centre, European Commission, The Netherlands

ARTICLE INFO

Article history:
Received 17 March 2015
Received in revised form
8 June 2015
Accepted 9 June 2015
Available online xxx

Keywords:
Hydrogen & fuel cell vehicle
High pressure storage tank
Defueling
Driving conditions
Safety temperature limit

ABSTRACT

During the driving of a fuel cell car, the expansion of the hydrogen along the emptying of the high pressure storage tank produces a cooling of the gas. The hydrogen vessel can experience a fast depressurization during acceleration or under an emergency release. This can result on the one hand in exceeding the low safety temperature limit of −40 °C inside the on-board compressed hydrogen tank and on the other hand in the cooling of its walls. In the present paper, defueling experiments of two different types of on-board hydrogen tanks (Type III and Type IV) have been performed in all the range of expected defueling rates. The lowest temperatures have been found on the bottom part of the Type IV tank in very fast defuelings. For average driving conditions, in both types of vessels, the inside gas temperature gets closer to that of the walls and the tank would arrive to the refuelling station at a temperature significantly lower than the ambient temperature.

Introduction

Following the declarations of the EU and G8 leaders, carbon dioxide emissions must be reduced by 80 per cent (from 1990 levels) by 2050. The targets are to stabilize the atmospheric carbon dioxide at 450 parts per million and to keep the increase in global temperature below 2 °C relative to its pre-industrial level [1]. To achieve these goals, the road transport sector would require a decarbonisation in up to a 95% [2].

Fuel cell electric vehicles (FCEV) provide the benefits of electric vehicles combined with the functionality of a combustion engine car. FCEV can be refuelled in 3–5 min using a fuel hose similar to the one used in a conventional fuel station. Moreover, they have autonomy for hundreds of kilometres before they need refuelling. Expected vehicle range per full fuelling is taken to be greater than or equal to 500 km (300 miles). The user convenience and the zero emission of FCEVs make them a clean alternative for personal transportation [3].

Consequently, many car manufacturers have stated their intention to commercialize fuel cell powered vehicles in the 2015/2020 timescale. In 2009 for example, seven of the largest car manufacturers in the world – Daimler, Ford, General Motors, Honda, Hyundai-Kia, Renault–Nissan and Toyota – signed a letter of understanding addressed to the oil and energy industries and government organizations. The letter indicated their intent to commercialize a significant number of FCEVs from 2015 [4]. Nowadays, some of these vehicles are already on the market: the Toyota Mirai [5] and the Hyundai ix35 [6].

Hydrogen is an energy dense fuel by mass, higher than conventional fuels. However, volumetric energy densities are much lower. At present, the most common method of storing hydrogen on-board in land vehicles is as a compressed gas,

---

* *Corresponding author.*

E-mail address: Nerea.DE-MIGUEL-ECHEVARRIA@ec.europa.eu (N. de Miguel).

http://dx.doi.org/10.1016/j.ijhydene.2015.06.038

either at 35 MPa or, more commonly, at 70 MPa. The hydrogen storage system contains all components that form the primary high pressure periphery for containment of stored hydrogen. The key functions of the hydrogen storage system are to receive hydrogen during fuelling, store the hydrogen until needed and then discharge the hydrogen to the fuel cell system for use in powering the vehicle. Constituents of a typical compressed hydrogen storage system include the high pressure hydrogen storage tank and all other components as the check valve, the shut-off valve and the thermally-activated pressure relief device (TPRD) [7].

Most high pressure hydrogen storage tanks used in fuel cell vehicles consist of two layers: an inner liner that prevents gas leakage/permeation and an outer layer that provides structural integrity. The liner is made of metal in a Type III tank and of plastic polymer in a Type IV. The outer layer is usually made of resin impregnated fibre reinforced composite which is wrapped over the liner. The on-board hydrogen storage system must fulfil specific performance based and technical design requirements [7–9] which are collected in regulations and standards for hydrogen powered motor vehicles.

The storage system must be able to supply a sufficient mass flow rate of hydrogen to the fuel cell system to meet the required power demand at acceptable pressures and temperatures under all driving conditions. The average fuel consumption of a hydrogen powered midsize crossover Sport Utility Vehicle (SUV) [10] can go from about 0.1 to 0.2 g/s for a city drive (30 km/h and 50 km/h; corresponding to about 10 kW fuel cell power) to 0.4–0.6 g/s for a highway drive (at 100 km/h and 120 km/h and about 30 kW fuel cell power). However, peaks of hydrogen consumption can be expected during acceleration; e.g. 0.7–0.8 g/s for an easy acceleration and 1.5–1.8 g/s for full-throttle acceleration. Moreover, the tank might also experience a very fast depressurization in an emergency hydrogen release from a TPRD which is designed to vent the entire contents of the vessel rapidly in a few seconds [7].

The transfer of hydrogen, which covers the filling and the emptying of hydrogen storage vessels, implies compression and expansion of the gas, which produces temperature variations. During the fast refuelling, the increase of the internal energy of the gas inside the tank (consequence of the work done to compress the gas) produces a temperature increase. Similarly, during the driving, the decrease of the internal energy of the gas produces its cooling. The hydrogen mass inside the tank is determined by the pressure and temperature. In order to take both parameters into account, the State of Charge (SOC) of a compressed hydrogen tank, given by Equation (1), has been defined as the ratio between the density of the gas at a given temperature and pressure and the full tank density (at 15 °C and the Nominal Working Pressure, NWP, which for our case is 70 MPa) [11].

$$SOC(\%) = \frac{\rho_{H_2}(P,T)}{\rho_{H_2}(NWP, 15^{\circ}C)} \cdot 100, \qquad (1)$$

Standards and regulations for on-board compressed hydrogen tanks have established that safe operational conditions, including filling and defueling, must respect the temperature limit between −40 °C and +85 °C [7–9]. The SAE J2601 standard [11] establishes the protocol for hydrogen fuelling of light duty vehicles. For non-communication case, the temperature of the vehicle storage system at the onset of fuelling is not available to the dispenser. This temperature is normally assumed to be equal to the ambient temperature. However, the storage system can be warmer or colder than ambient temperature at the start of refuelling. The reasons could be several; e.g. the vehicle parking location, the position of the storage system on the vehicle, the driving distance and speed to the refuelling point. In the last version of the standard, industry-wide consensus has been reached on the definition of “soak” as the temperature deviation from ambient of the vehicle storage system and “Hot Soak” and “Cold Soak” zones are specified as a function of the ambient temperature.

The GasTeF facility is a reference laboratory of the European Commission Joint Research Centre where pre-normative research on full-scale high pressure hydrogen tanks is performed in support to European Union policies [12]. In the last years, many experimental campaigns have been carried out in GasTeF to analyse on-board hydrogen tanks behaviour during refuelling. A description of the facility and some of the last obtained results can be found in Refs. [13–16]. In addition, the experimental results are complemented with computed fluid dynamics analysis of the phenomena taking place in the tank with a model developed at JRC by means of a ANSYS® CFX [17,18].

Although the refuelling of hydrogen is already a studied hydrogen transfer process, there are very few published data related to the behaviour of on-board hydrogen tanks during defueling. In the work presented in this article, a series of discharge experiments of commercial hydrogen storage tanks (one Type III and one Type IV) have been performed in GasTeF. The chosen defueling rates cover all the expected driving conditions; from a steady state city drive to the vehicle's maximum fuel-demand rate. Temperatures of the gas inside the tank have been monitored to study their spatial distribution. The temperatures at the outer surface have also been measured to study the temperature evolution through the walls and to determine its relation to the inside gas temperature.

Experimental conditions

In Table 1, the characteristics of the two 70 MPa nominal working pressure on-board hydrogen storage tanks used in this study are given. One is a Type IV with 29 L capacity and the other is a Type III with 40 L capacity. Similarly to our previous experimental studies [13–16], each tank has been instrumented with 8 thermocouples (TC) and with four resistance temperature detectors (RTD). The pressure has been measured using a pressure transducer (PT) placed at the rear. In all cases, a 3 mm diameter hydrogen injector has been used. As depicted in Fig. 1, the TCs (labelled TC1 to TC8) measure the temperature of the gas at different positions. The thermocouples have been placed inside the tank by means of a tree-shape array introduced through the rear. The RTDs (labelled TTop, TBottom, TFront and TRear) have been placed on the tank wall to measure the temperature of the external surface and of the bosses. The positions selected to compare the evolution of the inside gas temperature with the evolution

Please cite this article in press as: de Miguel N, et al., The effect of defueling rate on the temperature evolution of on-board hydrogen tanks, International Journal of Hydrogen Energy (2015), http://dx.doi.org/10.1016/j.ijhydene.2015.06.038