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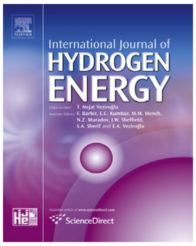

The role of initial tank temperature on refuelling of on-board hydrogen tanks

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ABSTRACT

The influence of the initial tank temperature on the evolution of the internal gas temperature during the refuelling of on-board hydrogen tanks is investigated in this paper. Two different types of tanks, four different fuel delivery temperatures (from ambient temperature refuelling to a pre-cooled hydrogen at −40 °C), several filling rates and initial pressures are considered. It has been found that the final gas temperature increases linearly with the increase of the initial tank temperature while the temperature increase (ΔT) and the final state of charge (SOC) decrease linearly with increasing the initial temperature. This dependency has been found to be larger on type III than on type IV tank and larger the larger the initial pressure. Additionally CFD simulations are performed to better understand the role of the relevant phenomena on the gas temperature histories e.g. gas compression, gas mixing, and heat transfer. By comparing the results of calculations with adiabatic and diathermal tank walls, the effect of the initial gas temperature has been separated from the effect of the initial wall temperature on the process.

Introduction

The need for reducing greenhouse gas emissions and the limitation of available non-renewable energy resources make compulsory the use of alternative fuels. Hydrogen, with higher energy content per unit mass than any known fuel can play an important role as a future energy carrier. In the transportation sector, fuel cell vehicles (FCV) powered by hydrogen could replace the traditional oil-derived fuel cars. However, there are still several barriers including hydrogen production, distribution, refuelling and the vehicle design itself which impede its massive diffusion in the automotive sector [1]. Regarding hydrogen storage, specific on-board storage technologies are necessary to match the typical energy densities of the traditional liquid fuels (gasoline or diesel). Currently, the most commonly adopted storage solution by car manufacturers is compressed hydrogen storage [2]. Gaseous hydrogen is stored on-board the vehicle in fully wrapped carbon fibre reinforced tanks. In order to reach high hydrogen densities, the gas is stored at high pressures. Hydrogen tanks with a nominal working pressure (NWP) of either 35 or 70 MPa are already in the market. Two types of liners are typically used in these tanks: metal in type III tanks and a polymer liner in type IV tanks [3].

The refuelling of on-board hydrogen tanks has to be performed in a reasonable amount of time. According to the European Fuel Cells and Hydrogen Joint Undertaking (FCH-JU),

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one of the technological challenges for the successful implementation of FCVs is to reduce the refuelling times to 3–4 min for passenger cars [4]. This is in line with the technical system targets for 2020 of the United States Department of Energy (DoE) for light duty fuel cell vehicles which set to 3.3 min the fuelling time of a 5 kg hydrogen on-board storage system [5]. During the refuelling, the compression work leads to a warming of the gas inside the tank. The final temperature within the tank can have an impact on the safety (tanks are designed to work between −40 °C and 85 °C [6–8]) but also on the level of filling of the tank; for the same pressure, the higher the temperature the lower the gas density. The level of filling is characterized by the State of Charge (SOC) which represents the ratio (in percentage) between the density of hydrogen inside the tank and its density at the NWP and 15 °C (40.2 kg/m^3 at 70 MPa NWP) [2]. To be able to refuel a vehicle in a practical amount of time without reaching the temperature limits and with a reasonable level of filling, the Society of Automotive Engineers (SAE) has established the SAE J2601, a standard for hydrogen fuelling protocols [9]. The SAE J2601 proposes refuelings based on a look-up table approach. The process limits (including the target pressure and pressurization rate) are determined by aspects such as ambient temperature, fuel delivery temperature, the size and the initial pressure of the compressed hydrogen storage system (CHSS). The CHSS consists of all the components that form the primary high pressure boundary for containment of compressed hydrogen including one or more than one tank depending on the amount that needs to be stored and the particular vehicle design [6].

It is known that the parameters of the CHSS to be filled (namely size, materials and initial temperature and pressure) together with the filling conditions (such as filling rate, final pressure and gas delivery temperature) determine the temperatures reached inside the tanks at the end of the refuelling [10–12]. The initial temperature of a tank when refuelled is normally assumed to be the same to the outside temperature; however, it could be warmer or colder than the ambient. The tank can be for instance heated up to 25 °C higher than the surroundings during parking or driving if being heated by the sun's rays [2]. On the other hand, under average driving conditions, when continuously emptying a full tank down to 20% SOC and due to the cooling of the gas during the expansion, the on-board tanks of the car could arrive to the refuelling station at a temperature at least 20 °C lower than the ambient temperature [13]. These situations could result in refuelings where the temperature inside the tank is higher or lower than the expected one leading to overheating or overfilling of the tanks. To avoid this, hot soak and cold soak zones are considered in the 2014 version of the SAE J2601 [9].

The initial temperature of the tank (assuming the tank in thermal equilibrium with the ambient temperature at the beginning of refuelling), as originally found by Maus [10] and later confirmed by other authors [14,15], has a linear effect on the maximum gas temperature during refuelling. Maus found that when refuelling a 70 MPa type III tank, an increase of 1 °C in the initial temperature results in a growth of 0.8 °C in the maximum temperature. Zhao et al. [14] on the other hand found that when refuelling a 35 MPa type III tank, an increase of 1 °C in the initial temperature results in a 0.3 °C increase of the maximum temperature. The aim of the work presented in this article is to further investigate the influence of the initial tank temperature on the evolution of the gas temperature during hydrogen refuelling. Several refuelling experiments have been carried out in both type IV and type III tanks at several initial tank temperatures. In particular, we have investigated the case of refuelling with different hydrogen pre-cooling levels (different fuel delivery temperatures) for relatively high initial tank temperatures. To assist the interpretation of the experimental results and to perform experiments at conditions not achievable at the experimental facility, numerical simulations of hydrogen refuelling of one of the tested tanks have been also carried out with a Computational Fluid Dynamics (CFD) model.

Experimental

GasTeF facility

The Gas Tank Testing Facility, GasTeF, is a laboratory of the European Commission's Joint Research Centre which aim is the testing of compressed hydrogen tanks [16]. The tanks are placed inside a 380 L volume closed sleeve which at the same time is enclosed in a safety vessel. The sleeve is maintained under a continuous flow of nitrogen. The sleeve temperature can be modified from ambient temperature up to 85 °C by means of a resistance heating that surrounds it over its entire

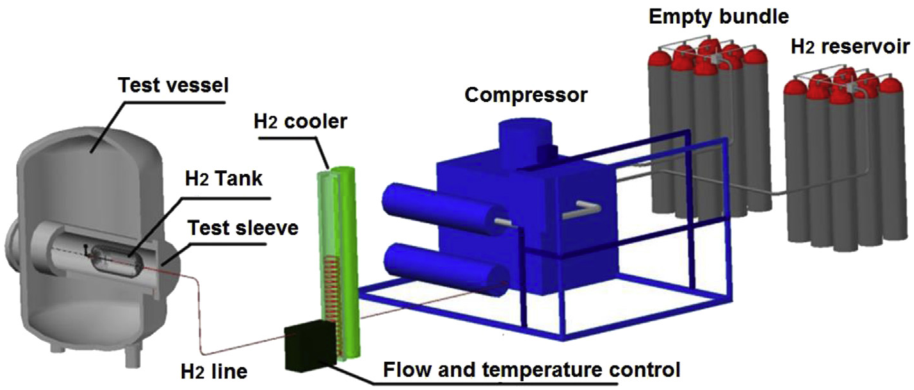

Fig. 1 – Scheme of the GasTeF facility.

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