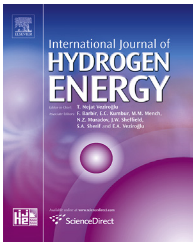
INTERNATIONAL JOURNAL OF HYDROGEN ENERGY 39 (2014) 582–592



Optimization of the overall energy consumption in cascade fueling stations for hydrogen vehicles

E. Rothuizen*, M. Rokni

Section for Thermal Energy Systems, The Technical University of Denmark, 2800 Kgs. Lyngby, Denmark

ARTICLE INFO

Article history:
Received 6 September 2013
Accepted 13 October 2013
Available online 9 November 2013

Keywords:
Hydrogen refueling
Energy consumption
Optimization
Dimensioning
Dynamic simulation

ABSTRACT

Hydrogen fueling stations are emerging around and in larger cities in Europe and United States together with a number of hydrogen vehicles. The most stations comply with the refueling protocol made by society of automotive engineers and they use a cascade fueling system on-site for filling the vehicles. The cascade system at the station has to be refueled as the tank sizes are limited by the high pressures. The process of filling a vehicle and afterward bringing the tanks in refueling station back to same pressures, are called a complete refueling cycle. This study analyzes power consumption of refueling stations as a function of number of tanks, volume of the tanks and the pressure in the tanks. This is done for a complete refueling cycle. It is found that the energy consumption decreases with the number of tanks approaching an exponential function. The compressor accounts for app. 50% of the energy consumption. Going from one tank to three tanks gives an energy saving of app. 30%. Adding more than four tanks the energy saving per extra added tank is less than 4%. The optimal numbers of tanks in the cascade system are three or four.

1. Introduction

Hydrogen refueling stations are emerging in and around the larger cities in Europe and The United States. The investors in Europe are primarily municipals or public funding who buys the stations to run with a set of hydrogen vehicles in the municipal service department. The latest example is Copenhagen municipality who bought a H2Logic 700 bar station to run with 15 Hyundai hydrogen vehicles. The reason to spend such huge investment was to promote hydrogen in the transport sector. In order for the public to accept hydrogen vehicles they need to be introduced into the market at platforms where they are highly visible and people slowly get used to the idea and the sight of them. Even though many stations are bought by municipalities to use with a number of hydrogen vehicles, the stations are often public and placed like any other common petrol station with public access. The new stations follows the protocol from society of automotive engineers for high speed hydrogen refueling within the safety limits of the storage tank in the vehicle, SAE J2601 [1]. In addition, the society of automotive engineers has made a protocol for an on-board vehicle system, SAE J2600 [2]. The two protocols allows the vehicle manufactures to build vehicles which can be refueled at any station and station manufactures to build station that can refuel any vehicle, as long as both complies with SAE J2600 and SAE J2601. The two protocols are developed in close cooperation with both vehicle and refueling station manufactures in order to secure a high implementation rate from the start. This is seen as the same vehicles are used in demonstrations worldwide with different refueling stations. The refueling procedure of vehicles is stated in the protocol, where the stated parameters are the

---

* *Corresponding author*. Tel.: +45 4525 4329; fax: +45 4588 4325.
E-mail address: edro@mek.dtu.dk (E. Rothuizen).

http://dx.doi.org/10.1016/j.ijhydene.2013.10.066

outlet temperature, the pressure ramp rate and the final pressure at which the refueling should end. These conditions depend on the ambient conditions and the type of tank in the vehicle. The protocol does not dictate or suggest how to reach the outlet conditions of the refueling station or what should happen after the refueling. Therefore the different hydrogen refueling station manufactures have different station designs. Though there are some similarities in the design of the refueling stations. First, they all cool the hydrogen before the exit. Second, the refueling is done using a cascade tank setup at the station. The cascade system consist of two to four different pressure levels, with the lowest starting from 350–500 bar the medium 500–700 bar and the highest typically above 900 bar. Third, there is a low pressure hydrogen bank at the station, 200–350 bar that can be used for recovering of the tanks in the cascade system. The pressures are typically chosen by the physical limitations of the tanks and the price. The high pressure tanks usually have a smaller volume than the low pressure tanks and a larger price tag. It is therefore beneficial with small high pressure tanks from an investment cost perspective, but the energy consumption of refueling the tanks in the cascade system is not known. The refueling of the cascade system at the refueling station is done using compressors. Different types of compressors used in the system are reciprocating compressors which also is the most common one, as well as ionic liquid compressors and membrane compressors. They are typically compressing in two or more stages and the hydrogen needs to be cooled down during, or after the compression. The whole process of refueling a vehicle and afterward bringing the used tanks in the cascade system back to starting pressure for a new refueling, is referred to as a complete refueling cycle. A complete refueling cycle is yet unexplored with regards to deciding number of tanks in the cascade system and the pressure and sizes of them. Farzaneh-Gord et al. have done research in entropy generation and entropy optimization between using on buffer tank and a three tank cascade system and found that a cascade fueling had the least exergy destruction but it also had the longest fueling time [3]. Hosseini et al. have done a similar exergy analysis of using one buffer tank for refueling compared to a cascade system, they also concluded that the cascade system had the least exergy destruction [4]. This paper considers the trade-off between number of tanks, sizes of the tanks and the pressure levels in the tanks, from an energy consumption point of view. It includes the total energy consumption from all the major components in a refueling station, the compressor and the refrigeration facilities. The thermodynamic model used for simulation of the refuelings uses first law equations and the tanks are modeled accounting for heat loss. The hydrogen gas is considered as a real gas and the compression is adiabatic, giving the worst case scenario with regards to the temperature development of hydrogen due to the compression.

2. Theory

The following section describes the theory used for the model of a hydrogen refueling station. The section consist of four parts; Governing equations for the tanks, governing equations for isotropic adiabatic compression, heat transfer and pressure loss equations and at the end a model description. The theory which is different from the previous paper on “Optimization of hydrogen vehicle refueling via dynamic simulation” [5] is mainly the two first parts about the tank and the compression. The third part covers; heat transfer equations, pressure loss equations and calculation of cooling demand.

2.1. *Governing equation for the tanks*

Moving hydrogen from a low pressure tank to a higher pressure requires mechanical work which in this case is a piston compressor. Further two tanks in which the hydrogen is stored needs to be present. The system can be split up into three main components; the compressor, the tank at the suction side and the tank at the discharge side. For deciding the properties inside the tanks during a complete cycle, both discharging and charging, the energy balance is done using first law analysis and using the equations for enthalpy instead of internal energy. This is necessary for the model to be able to both discharge and charge the tank within the same simulation. The energy balance in terms of internal energy for the tanks is:

$$\frac{dU}{dt} = h\frac{dm}{dt} + \frac{dQ}{dt} \tag{1}$$

where dU/dt is the change in internal energy, h is the enthalpy, dm/dt is the change in mass and dQ/dt is the heat rate entering or leaving the tank. The internal energy is $U = H - pV$ which is the enthalpy (H), the pressure (p) and the volume (V). Rewriting and substituting internal energy with enthalpy into eq. (1) gives:

$$\frac{dh}{dt} = \frac{1}{M}\cdot\left(h_{out}\cdot\dot{m} - h\cdot\dot{m} + V * \frac{dP}{dt} + \frac{dQ}{dt}\right) \tag{2}$$

This gives the energy balance expressed through change in enthalpy. The mass flow is expressed through the change in density in the volume, eq. (3).

$$\frac{dm}{dt} = \frac{d\rho}{dt} * V \tag{3}$$

where $d\rho/dt$ is expressed through differentials of enthalpy and pressure [6].

$$\frac{d\rho}{dt} = \left.\frac{\partial\rho}{dP}\right|_h \cdot \frac{dP}{dt} + \left.\frac{\partial\rho}{dh}\right|_P \cdot \frac{dh}{dt} \tag{4}$$

The total mass in the system can be found from

$$M = V\cdot\rho \tag{5}$$

For an adiabatic thermodynamic model of a tank which describes the energy change through enthalpy, eqs. (2)–(5) are needed to be in present. The heat leaving or entering the tank is not necessary, but it is of importance as it influences the properties of the hydrogen in the tank. A more detailed model with the heat transfer is thus preferred. For the system to be dynamic a controlling equation describing the flows between the tanks should also be present. The controlling equation can either be a function of mass flow change or pressure change.