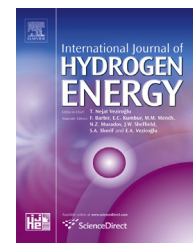


Available online at [www.sciencedirect.com](http://www.sciencedirect.com)

ScienceDirect

journal homepage: [www.elsevier.com/locate/he](http://www.elsevier.com/locate/he)

# Gas tank fill-up in globally minimum time: Theory and application to hydrogen



Fernando Olmos, Vasilios I. Manousiouthakis\*

Department of Chemical and Biomolecular Engineering, Hydrogen Engineering Research Consortium (HERC),  
University of California at Los Angeles (UCLA), Los Angeles, CA 90095-1592, USA

## ARTICLE INFO

### Article history:

Received 11 March 2014

Received in revised form

10 May 2014

Accepted 14 May 2014

Available online 24 June 2014

### Keywords:

Hydrogen

Compressed natural gas

Modeling

Optimal control

Global optimization

## ABSTRACT

The process of filling-up high-pressure gas storage vessels consists of a gas source tank, an isenthalpic (Joule–Thomson or J–T) valve, a cooling system, and a gas storage vessel. These units are assumed to be thermally insulated. The fill-up process is formulated as a minimum time optimal control problem. Despite the nonlinear nature of the aforementioned optimal control problem, its global solution is obtained analytically. A novel transformation technique is employed, to decompose the problem into a process simulation problem independent of time, and a simpler minimum time control problem that only depends on the final molar density value and the maximum allowable feed mass flowrate. The feasibility of the fill-up is uniquely determined by the process simulation problem, and upon fill-up feasibility, the minimum time control problem is then globally solved. Two fill-up case studies, involving two different system configurations are analyzed. In Case 1, the fill-up process has a constant molar enthalpy feed, and no cooling system. Case 2 considers a fill-up process with a constant temperature feed, delivered by an efficient cooling system. It was demonstrated that the optimal control strategy to achieve minimum fill-up time is to have the mass flowrate at its maximum allowable value during the entire duration of the fill-up. The presented problem formulation is general and can be applied to the fill-up of other gases, such as compressed natural gas.

Copyright © 2014, Hydrogen Energy Publications, LLC. Published by Elsevier Ltd. All rights reserved.

## Introduction

A significant issue faced by fueling stations that serve gaseous fuels, such as hydrogen and compressed natural gas (CNG), is to provide a rapid, complete, and safe replenishment of the fuel. In the case of gaseous hydrogen fuel, all fill-up specifications are subjected to a limitation of the gas storage vessel of hydrogen fuel cell car vehicles. From Ref. [1], type IV tanks with polyamide or plastic liner and carbon fiber wrap, may

exhibit mechanical failure if the temperature of the gas inside them is raised above 85 °C (358.15 K) during their repeated fill-ups. Consequently, it is required that during fill-up the gas temperature inside the vehicle tank be kept below the maximum temperature limit of 85 °C (358.15 K). Subject to this safety requirement, the fill-up needs to be performed in as short time as possible, so the end-user does not see the hydrogen car fill-up process as a hindrance, compared to the fill-up of gasoline cars.

\* Corresponding author. Tel.: +1 310 206 0300; fax: +1 310 206 4107.

E-mail address: [vasilios@ucla.edu](mailto:vasilios@ucla.edu) (V.I. Manousiouthakis).

<http://dx.doi.org/10.1016/j.ijhydene.2014.05.091>

0360-3199/Copyright © 2014, Hydrogen Energy Publications, LLC. Published by Elsevier Ltd. All rights reserved.

To address the aforementioned safety and time constraints, current hydrogen fueling stations slow down the hydrogen fill-up process or pre-cool the hydrogen below 0 °C so they can employ a higher hydrogen fill-up rate. For example, Ref. [1] refers to fill-ups of on-board 700.00 bar and 150 L type III and type IV tanks with warm and cold fill-up processes. The warm process of Ref. [1] filled-up to 90% of completion a type III tank in 3–4 min with hydrogen starting at ambient temperature; a fill-up to 100% completion required cooling down the hydrogen to temperatures around 0 °C (273.15 K). Both warm fill-ups avoided the hydrogen's temperature rise reaching 85 °C. The cold fill-up process reported in Ref. [1] was performed on a type IV tank, with hydrogen from the station storage tank pre-cooled to temperatures between 253.15 K and 233.15 K (–20 °C to –40 °C), and the fill-up carried out in 3–4 min. Ref. [1] also carried out a cold fill-up in less than 3 min, when hydrogen was pre-cooled to 188.15 K (–85 °C). Ref. [1] discusses hydrogen pre-cooling to liquid nitrogen temperatures, 77.00 K or –196.15 °C, for fast fill-ups. Likewise, Ref. [2] states that for fill-ups under 4 min, pre-cooling to temperatures from 248.15 K to 233.15 K (–25 °C to –40 °C) is required for 700.00 bar tanks, but pre-cooling may not be required for 350.00 bar tanks.

The fill-up of CNG cars faces similar issues to the ones described above for hydrogen. The typical pressure rating of CNG tanks is 250.00 bar (3600 psi). Ref. [3] describes two types of CNG fill-ups: fast-fill and time fill. A fast-fill of CNG can last 5 min and lacks control on the temperature of CNG during the

under which the fill-up can be performed in four to 1 min, without violating safety limits. The problem formulation is general and can be employed in commercial applications like fill-up of hydrogen vehicles, fill-up of CNG vehicles, and fill-up of high-pressure storage tanks.

## Conceptual framework and solution approach

### Thermodynamic modeling for real gases

Modeling the fill-up of high-pressure storage vessels with gases requires that a detailed thermodynamic model be employed for the gas phase. In this work, a gas phase that consists of only one chemical species is considered, and Gibbs' phase rule then suggests that two independent thermodynamic variables (in this work temperature ( $T$ ) and molar density ( $\rho$ )) are required to fully define the system state. The Generic Cubic (GC) equation of state is then employed to describe the dependence of pressure on these independent variables as follows:

$$P: \mathbb{R}^2 \rightarrow \mathbb{R}, \quad P: (T, \rho) \rightarrow P(T, \rho) \triangleq \frac{RT\rho}{1 - b\rho} - \frac{a(T)\rho^2}{(1 + \epsilon b\rho)(1 + \sigma b\rho)} \quad (1)$$

In addition, a self-consistent thermodynamic model for the gas molar internal energy, using residual properties and an ideal gas heat capacity model is employed, as described in Ref. [4] and shown below:

$$\begin{aligned} u: \mathbb{R}^2 \rightarrow \mathbb{R}, \quad u: (T, \rho) \rightarrow u(T, \rho) \triangleq & u^R + \ln\left(\frac{1 + \sigma b\rho}{1 + \epsilon b\rho}\right) \left[ \left( T \frac{\psi R^2 T_c}{P_c b(\sigma - \epsilon)} \right) \left( -0.5 \left( \frac{T}{T_c} \right)^{-1.5} \right) - \frac{1}{b(\sigma - \epsilon)} \frac{\psi R^2 T_c^2}{P_c} \left( \frac{T}{T_c} \right)^{-0.5} \right] \\ & - \ln\left(\frac{1 + \sigma b\rho^R}{1 + \epsilon b\rho^R}\right) \left( T^R \frac{\psi R^2 T_c}{P_c b(\sigma - \epsilon)} \left( -0.5 \left( \frac{T^R}{T_c} \right)^{-1.5} \right) - \frac{1}{b(\sigma - \epsilon)} \frac{\psi R^2 T_c^2}{P_c} \left( \frac{T^R}{T_c} \right)^{-0.5} \right) \\ & + (C_{pA}^0 - R)(T - T^R) + \frac{1}{2} C_{pB}^0 (T^2 - (T^R)^2) + \frac{1}{3} C_{pC}^0 (T^3 - (T^R)^3) + \frac{1}{4} C_{pD}^0 (T^4 - (T^R)^4) \\ & + \frac{1}{5} C_{pE}^0 (T^5 - (T^R)^5) \end{aligned} \quad (2)$$

fill-up process. On the other hand, a time fill can last several hours, is usually performed overnight, and provides complete control over the CNG temperature.

In this work, a novel solution methodology, that tackles the issues mentioned above, is proposed for the fill-up process of any high-pressure storage vessel. Based on a self-consistent thermodynamic, and conservation law based model described in Ref. [4], the fill-up process is formulated as a minimum time optimal control problem that incorporates all safety and efficiency concerns as problem constraints. Then, a novel transformation allows the decomposition of the minimum time control problem into a simulation problem that determines problem feasibility, and a time optimal control problem that can be analytically solved. Two fill-up cases are explored: gas fed at constant molar enthalpy and gas fed at constant temperature. The first case gives rise to a set of algebraic equations, while the second case gives rise to a differential-algebraic-equation (DAE) system. Finally, the solution methodology for both cases is applied to the case of a hydrogen fuel cell car fill-up, and conditions are identified

Then, the gas molar enthalpy is readily derived as:

$$h: \mathbb{R}^2 \rightarrow \mathbb{R}, \quad h: (T, \rho) \rightarrow h(T, \rho) \triangleq u(T, \rho) + P(T, \rho)/\rho \quad (3)$$

### Gas storage vessel fill-up model

Two gas storage vessel fill-up configurations are illustrated in Fig. 1a and b. The first does not employ a cooling system, while the second one does. They both employ the following pieces of equipment: gas source tank, isenthalpic (Joule–Thomson or J–T) valve, and gas storage vessel.

The following set of assumptions is employed in creating a model for the above system configurations:

- The overall process is adiabatic, so no heat transfer is allowed between any of the system components and the environment, at any point in time.
- The pressure of the isenthalpic valve outlet is equal to the pressure inside the gas storage vessel (whether a cooling system exists or not).

Download English Version:

<https://daneshyari.com/en/article/1273013>

Download Persian Version:

<https://daneshyari.com/article/1273013>

[Daneshyari.com](https://daneshyari.com)