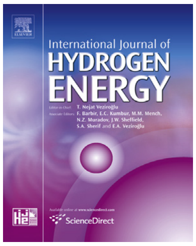
INTERNATIONAL JOURNAL OF HYDROGEN ENERGY 40 (2015) 11748–11755

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/he



Evaluating the temperature inside a tank during a filling with highly-pressurized gas

Thomas Bourgeois[*], *Fouad Ammouri*, *Mathilde Weber*, *Christophe Knapik*

Paris-saclay Research Center, Air Liquide, France

ARTICLE INFO

Article history:
Received 21 November 2014
Received in revised form
14 January 2015
Accepted 20 January 2015
Available online 27 February 2015

Keywords:
Hydrogen dispenser
Temperature estimator
Soft-sensor
Modeling
Safety
Filling

ABSTRACT

Gas storage of hydrogen in composite pressure vessels at high pressure is attractive for weight reasons. On the other hand, filling in a short time has to be properly controlled to insure safety. Indeed, compression effects during the H_2 fast filling of a cylinder induce a temperature rise inside the gas whose level depends on filling rate, thermal properties of the walls and also geometric characteristics of the cylinder. The effect of each parameter must be well understood to optimize filling quality while maintaining safety. This study presents experimental results obtained on a type IV 90.5 L tank for different filling conditions. Temperatures of the gas have been monitored during filling using temperature sensors. A soft sensor (0D model) has been developed for real time gas temperature estimation during filling. Comparisons between numerical simulations derived from this soft sensor and experimental results are discussed in order to prove the validity of the model and provide a deeper understanding of thermal phenomena in the cylinder.

Introduction

Dependency of our economies on fossil fuels may generate serious issues in our near future. Processes of rarefaction and CO_2 pollution could lead to repeated economic crises and potential global warming. In this context, hydrogen energy is still one of the most promising alternatives to petrol and natural gas.

Recently, weight issues have lead to the use of composite tanks rather than metallic ones for the storage and transport of hydrogen. On the other hand, manufacturers of composite tanks recommend not exceeding temperatures of 85 °C in their materials for safety reasons, but it is a well-known fact that the compression of a gas during filling of tanks causes temperature increase.

Therefore, being able to evaluate the hydrogen temperature elevation is of high value. However, direct measurement with thermocouples of the temperature of a gas inside a tank in an industrial context (e.g. a gas filling center or a car fueling station) is not straightforward and requires complex and expensive infrastructure. It is the purpose of this paper to present a method of calculating the temperature rise of a gas through simple thermodynamical modeling and measures of critical parameters such as the pressure of the tank and the temperature of the inlet gas.

Previous scientific studies have paved the way for this work.

Experimental works have permitted to study general tendencies of the average gas temperature during fillings. [1–3] studied the impact of tank liner material on heat exchanges and found that higher temperatures are reached in type IV

---

[*] *Corresponding author*. Tel.: +33 (0)1 39 07 60 19.
E-mail address: thomas.bourgeois@airliquide.com (T. Bourgeois).

http://dx.doi.org/10.1016/j.ijhydene.2015.01.096

Nomenclature

c_p	specific heat capacity of the gas at constant pressure, J kg^{-1} K^{-1}
$c_{p,w}$	specific heat capacity of the wall, J kg^{-1} K^{-1}
d_{in}	diameter of the injector of the tank, m
D_{int}	internal diameter of the tank, m
ε	tank emissivity
g	acceleration due to gravity, m s^{-2}
h	specific enthalpy of the gas, J kg^{-1}
h_e	specific enthalpy of incoming gas, J kg^{-1}
k_a	external heat exchange coefficient between the wall and the ambient, W m^{-2} K^{-1}
k_g	internal heat exchange coefficient between the wall and the gas, W m^{-2} K^{-1}
L_{int}	internal length of the tank, m
m	mass of gas within the tank, kg
$\dot{m}$	mass flow rate into the tank, kg s^{-1}
m_w	mass of the wall, kg
Nu_{Dint}	Nusselt number of the gas, dimensionless $Nu_{D_{int}} = \frac{D_{int} k_g}{\lambda_{gas}}$
P	pressure of the gas, Pa
Pr_{air}	Prandtl number of the air, $\mathrm{Pr}_{air} = \frac{\mu_{air}\ c_{p_{air}}}{\lambda_{air}}$
R	ideal gas constant, J mol^{-1} K^{-1}
Ra_{Dint}	Rayleigh number of the gas, $Ra_{D_{int}} = \frac{g\beta\lvert T-T_{wi}\rvert c_p \rho^2 D_{int}^3}{\mu\lambda}$
$Re_{d_{in}}$	Reynolds number of the flow, $Re_{d_{in}} = \frac{\rho w d_{in}}{\mu} = \frac{4\dot{m}}{\pi\mu d_{in}}$
$Re_{D_{ext}}$	Reynolds number of the air $Re_{D_{ext}} = \frac{\rho_{air} V_{air} D_{ext}}{\mu_{air}}$
S_e	external surface of the tank, in contact with ambient atmosphere, m^2
S_i	internal surface of the tank, in contact with gas, m^2;
T	temperature of the gas inside the tank, K
T_{amb}	ambient temperature, K
T_{fe}	temperature of the air, in contact with the external wall of the tank, K
T_{fi}	temperature of the gas, in contact with the internal wall of the tank, K
T_w	temperature of the wall, K
T_{we}	temperature of the wall, in contact with the air, K
T_{wi}	temperature of the wall, in contact with the gas, K
V	volume of the tank, m^3
υ	specific volume of the gas, m^3 kg^{-1}
w	velocity of gas at inlet, m s^{-1}
Z	compressibility factor of the gas, used in the real gases law, dimensionless
β	thermal expansion coefficient of the gas, K^{-1} $\beta = \frac{1}{\upsilon}\left(\frac{\partial \upsilon}{\partial T}\right)_P$
ε	emissivity of the external surface of the tank, dimensionless
λ	thermal conductivity of the gas, W m^{-1} K^{-1}
μ	dynamic viscosity of the gas, Pa s
ρ	density of the gas, kg m^{-3}
σ	Stefan-Boltzman constant, W m^{-2} K^{-4}

tanks (plastic liner) than in type III tanks (metalic liner). Studies by Refs. [4–7] have shown that high filling rates cause a higher increase of the average temperature. Effect of the ambient temperature and inlet temperature on the final gas temperatures have been studied by Refs. [1] and [8].

Simple thermodynamical modeling of the filling of a gas was first performed by Reynolds and Kays in 1958 [9]. They derived a certain number of closed-form solutions for special cases of filling which provide better understanding of parameters involved in the rise of gas and wall temperature. [10–12] suggested further analysis with the possibility of having real-gas behavior, while [13] pointed out the importance of kinetic energy at the inlet [1]. added precision to the modeling of the wall (one-dimension modeling across the radius of the tank), as did [2] and [14].

We also underline the great step forward that has been taken with the possibilities offered by Computational Fluid Dynamics. Dicken and Merida proposed in 2006 a first comparison of 2D simulations with experiments fillings ([15], [4]). Since then, the Joint Research Center of the European Commission proposed 3D simulations ([16]) and several other numerical studies have been performed by others ([17–22]) to study the impact of the filling conditions and tank parameters on the gas and wall temperatures, velocity fields and subsequent heat exchanges between the gas and wall. Still, it must be recalled that CFD computing is very time-consuming: orders of duration for a single calculation on a regular computer being between a day for a 2D simulation, to a month for a 3D simulation. Therefore, CFD computing cannot be applied to real-time temperature estimation.