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A thermodynamic analysis of refueling a Natural Gas Vehicle cylinder from a cascade reservoir using chilled natural gas

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ABSTRACT

The aim of this study was to simulate the refueling of a Natural Gas Vehicle (NGV) Cylinder from a Cascade Reservoir using chilled Natural Gas. The model was developed using the First Law of Thermodynamics, Mass balances and Gas Dynamics laws. Three distinct Cascade Reservoir temperatures were selected for simulations for this study; 288 K, 291 K and 293 K respectively. Simulations were conducted employing various initial NGV Cylinder parameters (Temperature and Pressure). The empirical findings from the simulations showed that the use of chilled Natural Gas to refuel an NGV Cylinder resulted in a reduced temperature increase during refueling in the order of 50 K-60 K as opposed to 70 K-80 K when refueling at ambient temperature. It was also observed that when using chilled natural gas to refuel, the initial cylinder temperature had no effect on the overall refueling process. However, varying initial cylinder pressures had a significant effect.

Fill ratios obtained using the chilled gas were greater than refueling at ambient, however it was expected that using chilled gas fill ratios would be greater than 80%, this was not observed. The highest fill ratio obtained was 70.13%. Further analysis on the performance of the reservoir temperatures selected showed that the lower reservoir temperatures mitigated the effects of the Heat of Compression during refueling far better than refueling from ambient. This manifested in reduced in-cylinder temperature rise during refueling and higher fill ratios at completion of fill. Therefore, it was concluded that the Reservoir Temperature (T_{res}) has the greatest effect on the refueling process and lower Reservoir Temperatures are key to obtaining fill ratios >80%. Further study is definitely required into this novel method of obtaining a quality fill with CNG.

1. Introduction

Today, the transport sector faces a paradigm shift. That shift is towards the use of alternative fueled vehicles (AFV's). This change is a direct result of the growing scarcity of oil, more stringent vehicle emission standards and climate change (due to global warming). In today's world there are numerous alternative fuels being employed in the transport sector. Some of these alternative fuels include: 1. Compressed Hydrogen Gas (CHG) 2. Electricity 3. Bio-Diesel 4. Propane 5. Ethanol 6. Compressed Natural Gas (CNG) and 7. Liquefied Natural Gas (LNG). In addition to these, research and development is currently being carried on new emerging alternative fuels like Di-Methyl Ether (DME) or Methanol for future introduction to the market (U.S Department of Energy, 2016).

This study seeks to take a closer look at one alternative fuel in particular; Compressed Natural Gas (CNG). Natural Gas as a transportation fuel is a gaseous, colourless, odourless and non-corrosive mixture constituting mainly of Methane (85% mol. or higher) with trace amounts of Ethane, Propane, Butane, Pentane, Hexane, Nitrogen, Carbon Dioxide and Water. Storage of Natural Gas at atmospheric conditions is unfeasible due to the large volume required to be stored to attain comparative driving distances as with liquid fuel vehicles. Being a gas at ambient temperatures, the fuel can be subjected to compression and storage under high pressures. This would ensure that enough methane is stored to achieve adequate driving distance. Natural Gas is compressed and stored usually at 20.684 MPa (approximately 3000psi) within the on-board vehicular storage, however in some countries their operating standards allow CNG Cylinders to be filled to 3600psi so that more gas is stored (ANSI (American National Standards Institute), 2007; BioCNG, 2014).

The wider acceptance of CNG against its liquid fuel counterparts

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such as petrol or diesel has been plagued with a number of problems. Some of the major problems are as follows:

1. Lengthy refueling time;
2. Loss of power (torque) from engine;
3. Inadequate driving range between refueling periods.

In this study, the under filling problem will try to be remedied via the use of chilled natural gas to refuel the on-board storage cylinder from the cascaded storage banks as opposed to CNG at ambient temperatures as is the norm. The objective of this study is to model and simulate refueling of an NGV storage cylinder using chilled gas from a cascade storage reservoir, while monitoring pressure and temperature variations in cylinder and the amount of gas charged to the cylinder upon completion of refueling.

The core hypothesis being tested is that the use of chilled gas during refueling reduces the temperature rise during refueling and increases the charged mass to the cylinder upon completion of fill. This analysis is conducted mainly on a theoretical basis, the practical and economical analysis of chilling and/or storing this chilled gas in the station will not be in the scope of this research.

2. Literature review

Among the key parameters affecting the driving range of a Natural Gas Vehicle (NGV) as indicated in the study carried out by Farzaneh-Gord et al., (2012) is the storage capacity of the on board cylinder. It is therefore essential that the storage cylinder(s) be optimally filled during the refueling process. Many observations of the refueling process showed that the temperature of the gas within the cylinder increases in the order of 40 °C–70 °C depending on the presiding ambient temperatures at the time of refueling (Farzenah-Gord, 2009). The cause of this temperature rise has not been thoroughly studied to date. However, from the literature reviewed, the temperature rise can be attributed to the mixing and compression of the gas being charged into the cylinder with the gas already present in the cylinder (Farzenah-Gord, 2009). This increase in temperature of the gas within the cylinder has a two pronged effect; the increased temperature reduces the density of the gas and secondly, from the general Pressure Law, the Pressure of a gas is proportional to its Temperature. As the gas temperature increases, the pressure in tandem increases rapidly and consequently it attains its maximum charge pressure 20.684 MPa (3000psi), at which point refueling is completed. Post refueling the gas dissipates its heat through the cylinder walls to the atmosphere to return to ambient temperature. Both the density of the gas and pressure within the cylinder fall and ultimately the cylinder is left under filled. This phenomenon significantly reduces the driving range of the NGV and ultimately impacts negatively the greater acceptance of CNG as an alternative fuel (Deymi-Dashtebayaz et al., 2011; Farzenah-Gord et al., 2007).

Efforts to find a solution to this under filling problem have been investigated in the past via two aspects. The first by investigating the effect of refueling on the CNG Cylinder itself and the second by optimising the performance of the CNG station so a better fill is obtained.

Compressed Natural Gas (CNG) is stored on-board NGV's via gas tight cylindrical pressure vessels made of various materials. There are varying sizes of cylinders in terms of volumetric capacities available on the market today. The size of cylinder chosen is based upon the desired driving range of the NGV and the availability of space for cylinder(s) on board the vehicle. Due to the bulky size of these cylinders, a single large cylinder may not be the preferred solution given the availability of space and the architecture of the vehicle. Therefore, in order to maximise the driving range of the vehicle, a combination of cylinders of the same size or varying sizes may be utilized all of which are connected in series.

Of the NGV population in Trinidad and Tobago, only Type I (all steel) cylinders are currently utilized. For this study, the CNG cylinder to be charged is a 67 L Type I cylinder made of 34CRMO44 steel, the relevant dimensions of the cylinder can be seen in Fig. 1.

Much of the existing work on this topic centres on a single reservoir (gas storage), very few studies attempted to model the refueling of an NGV cylinder using a Cascade storage regime. The first study was carried out by Farzaneh-Gord et al. (2008a), it consisted of a thermodynamic analysis of refueling a CNG cylinder via the use of cascade reservoirs. The thermodynamic model utilized was similar to that of Farzaneh-Gord et al. (2009) above. The findings showed that the largest in-cylinder temperature increase during the refueling process was observed when refueling took place from the 'Low' bank and that the Joule-Thompson effect was only observed when refueling commenced from the 'Medium' and 'High' banks (Farzenah-Gord et al., 2008). Unlike with the single storage studies, where the gas reservoir was maintained at station pressure (>20 MPa), the 'low' bank storage is not kept at station pressure but considerably lower. Therefore, when refueling commences the Joule-Thompson effect is not significant enough to overcome the heat generated when the charged gas supply enthalpy converts to internal energy within the cylinder. When refueling from the 'Medium' and 'High' banks, the temperature reduction due to the Joule-Thompson effect is quite significant and this restricts the rapid temperature rise of the gas until refueling has completed.

The study however did not investigate the effect of varying the initial in-cylinder pressure on refueling. Most of the simulations were run using a virtually empty cylinder. Arising from the study by Farzenah-Gord et al. (2008a) and Farzenah-Gord et al. (2008b), Farzenah-Gord and Deymi-Dastebayaz (2013) conducted research to optimize the station performance based on the pressure maintained in the cascade system to ensure adequate, efficient refueling. The model developed was based on the isentropic expansion across an orifice and an ideal gas model was utilized. For the purposes of the study the storage reservoirs were assumed to be infinite. The pressure profile during refueling resembled those obtained from the study carried out by Farzenah-Gord et al. (2008b), with the three discontinuities when switching between cascade banks. The temperature profile of the CNG cylinder during refueling resembled a rapid climb and then a plateau until refueling was completed. The temperature profile took this form since an ideal gas model was

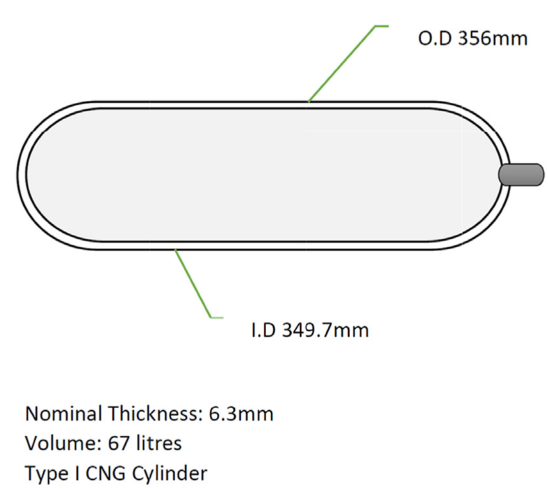

Fig. 1. Schematic of CNG cylinder.