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Dynamic Modeling of a Compressed Natural Gas Refueling Station

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Abstract

Compressed Natural Gas (CNG) is one of the alternative vehicle fuels. Benefits of CNG include cost savings, reduced emissions, ease of vehicle maintenance, and increased energy security. CNG is stored in high pressure cylinder on the vehicle which calls natural gas vehicle or tank (NGV). There are two types of CNG infrastructure; time-filling and fast-filling process. At the fast-filling process, desired filling time is less than 300 s. At the CNG refueling stations, natural gas compressed by compressors and storage in the high-pressure reservoir tanks. During refueling, natural gas vehicles (NGV) are connected to the high-pressure reservoir tanks by a dispenser. While dispensing the fuel, the temperature and pressure changings must be controlled. To understand these changes, in this study a CNG Refueling station is modelled in Matlab/Simulink/Simscape. Model is used with ideal gas and real gas assumptions.

Keywords: Compressed Natural Gas, Matlab/Simulink/Simscape Modelling.

I. Introduction

Compressed Natural Gas (CNG) is a clean alternative fuel rather than gasoline and diesel. Natural gas vehicles (NGV) receive CNG from high-pressure storage tanks to their fuel cylinder at refueling stations. During filling NGV cylinder temperature rises. This temperature rise reduces the density of the gas in the cylinder, resulting in an under-filled cylinder. If this temperature rise is not compensated in the fuelling station, the vehicle driving range will reduce. To control the temperature rises, time-filling process can bu used. The NGV industry tries to provide a system to refuel a NGV comparable to a gasoline dispenser. To be comparable to the fill time is taken to fill a gasoline powered automobile. This fill time can be referred to as a fast fill or rapid charge which is under 300 seconds.

At CNG refueling stations one of the most important equipment for producing high pressure gas is reciprocating compressors. In order to reduce electricity consumption in CNG stations, (Yong-Liang et all., 2021) regulated the frequency of activation of the compressor (which consumes the most electricity) using genetic algorithm models. Flow chart of CNG base station: filtration, dehydration, compressor, storage. They modeled: prefilter, dehydration device, compressor, expansion tank, storage tanks, dispenser. Genetic algorithm models were solved with the help of matlab. Gas masses for the tank are considered as 250, 350, 450 kg. The buffer tank is designed to hold 200 kg of gas.

Ideal and real gas assumption models are important to see the difference. (Farzaneh-Gord et al., 2015) The models are solved with the AGA8 equation of state (EOS). The piston compressor is the most important element of the system and the affecting factors are; angular velocity, cut-in, pressure ratio. The temperature in the control volume is higher in the ideal gas, the mass flow rate and work are higher in the real gas, and the work done for the compressor is higher in the ideal gas. With a 3 or 4 stage piston compressor, 20 and 25 MPa pressure can be reached. The biggest expense in CNG stations is the energy supplied to the compressor. Therefore, optimizing the compressor parameters, achieving high efficiency and low work input is the main goal. To achieve this, volumetric effectiveness, work done per mass and reduced efficiency are calculated by making changes in 5 main and 4 second dimensionless parameters.

There are three objectives for the development of CNG stations. (Farzaneh-Gord et al., 2016) Filling time minimization, filling of storage tanks and maximization of usability rate. Two types of storage systems are used in CNG stations. single and multiple storage system CNG flow is modeled as one-dimensional and isothermal flow for both the vehicle interior and storage tanks. The system can be thought of as storage tanks, connection pipes, dispenser, and vehicle tank. The multiple storage system is divided into low, medium and high-pressure tanks. Filling is done first with low storage tanks. The vehicle tank is increased to 200 bars. Then medium and high-pressure tanks can come into play. AGA8 EOS general form as long as the mass flow rate is above 0.02 kg/s, vehicle tank filling will take less than 5 minutes. High pressure 500 liters, medium pressure 1000 liters, low pressure 1500 liters are suitable. Starting reservoir tank pressures are 230 bar.

According to the results of the study, (Deymi-Dashtebayaz et al., 2012) the initial pressure of the storage tank has a great impact on increasing the vehicle tank to the targeted pressure (20 MPa). The results showed that the effect of ambient temperature on filling is very large. Especially to the final condition of the vehicle tank and storage tank. Mass transfer is thought to be direct from the storage tank to the vehicle tank. The control volume is considered for both the storage tank and the vehicle tank. The continuity equation, that is, the conservation of mass, the first law of thermodynamics, was solved by considering two control volumes and was concluded with the assumption of an adiabatic cylinder surface. The second law of thermodynamics for entropy was derived with the same assumptions. Storage tank drops from 234 to 226 bar. Vehicle tank increases from 0 to 8 kg.

According to the results of the study, (Farzaneh-Gord et al., 2014) the components that make up natural gas have a significant impact on the filling process and the final state of the fuel tank. Moreover, compounds with less methane gas are more suitable for filling. Standard usage for CNG vehicles is to fill the fuel tank at 20 or 24.5 MPa pressure. Due to overheating during filling, the filling test is performed at higher pressure and the value allowed by ISO 11439 is 26 MPa, regardless of the external temperature. Maximum values are determined so that the tank cylinder can be filled 1000 times a year and can be used for 20 years. The operating temperature is expected to be between -40 and 65^0 C and rises to a maximum of 82^0 C. In previous studies, natural gas was assumed to be pure methane or a fixed mixture, and the effects of different natural gas mixtures on the filling process and the

values of the final cylinder tank were not examined. The aim of this study is to examine this effect for buffer storage systems.

In this study, a dynamic model is constructed for the designed CNG refueling station and simulated by MATLAB/Simulink/Simscape program. Pressure and temperature changes are investigated.

II. System Description

The schematic view of the designed system is shown in Fig. 1. The model consists of pipeline, 3 stages compressor, buffer reservoir tanks, a dispenser and a vehicle cylinder. Those 5 subsystems are controlled by control logic state flow. This state flow decides the timing of the natural gas flow from pipeline to vehicle.

The pipeline subsystem contains solver configuration and natural gas properties for begining, entering and custody metering of the gas to the station. The ideal and real gas assumptions are made here.

Multistage compressor subsystem contains 3-stage reciprocating compressor and cooling system. All stages of the compressor pressure ratio are 3. There are 2 intercooler and 1 aftercooler. Cooling fluid is water and it cools with fan air.

Buffer tanks subsystem contains reservoir tanks. For this model tanks total volume is chosen 960 liters.

Dispenser subsystem contains reduce valf to dispatch the CNG to the cylinder. There is a hose between dispenser and cylinder to add impact the friction of the pipes.

Vehicle tank subsystem contains a cylinder tank. There are mass, pressure and temperature sensors. Tank volume is 70 liters.

For this study natural gas assumed pure methane.The models aim is basicly to reach the buffer and vehicle tanks pressure to 250 and 200 bar respectively.

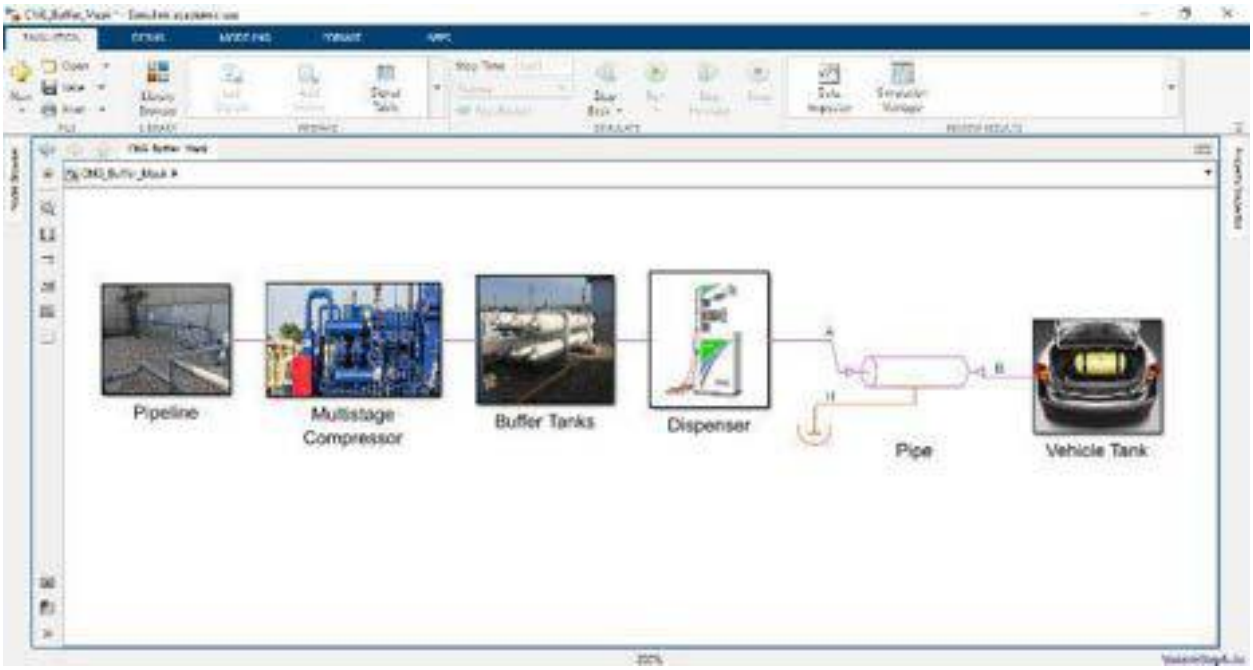


Fig. 1. Designed Model

III. Analysis

To model the fast filling process, vehicle cylinder is considered as a simple thermodynamic control volume. Applying the mass conservation principle to the control volume, the conservation of mass equation may be written as follow:

$$\dot{m}_i = \frac{dm_c}{\mathrm{dt}} \tag{1}$$

where m_i is inlet mass flow rate. The general form of the first law of thermodynamics for an open system yields:

$$\dot{Q_{cv}} + \sum \dot{m}_i \left(h_i + \frac{{V_i}^2}{2} + gz_i\right) = \sum \dot{m}_e \left(h_e + \frac{{V_e}^2}{2} + gz_e\right) + \frac{d}{dt}\left[m(u + \frac{V^2}{2} + gz)\right]_{cv} + \dot{W_{cv}} \tag{2}$$

The change in kinetic and potential energy and the work term could be neglected. Above equation could be simplified:

$$\frac{dU_c}{dt} = \dot{Q_{cv}} + \dot{m}_i \left(h_i + \frac{{V_i}^2}{2}\right) \tag{3}$$

IV. Results and discussion

In CNG station model results are shown in Figure 2.The results is determined for real gas assumption.The NGV cylinder initial pressure is 10 bar when the filling process is completed the final pressure of the NGV cylinder increases to 193 bar. The temperature of NGV

cylinder rises 82^0 C from 25^0 C. The mass flow into the NGV cylinder is between 0.044 – 0.03 kg/s. The buffer tank initial pressure is 20 bar and the compressor shut down when the final pressure of the buffer tank increases to 255 bar at nearly 17 minutes. The temperature of buffer tank rises $41{,}5^0$ C from 25^0 C. Total mass of the CNG in cylinder is 7,4 kg in nearly 4 minutes.

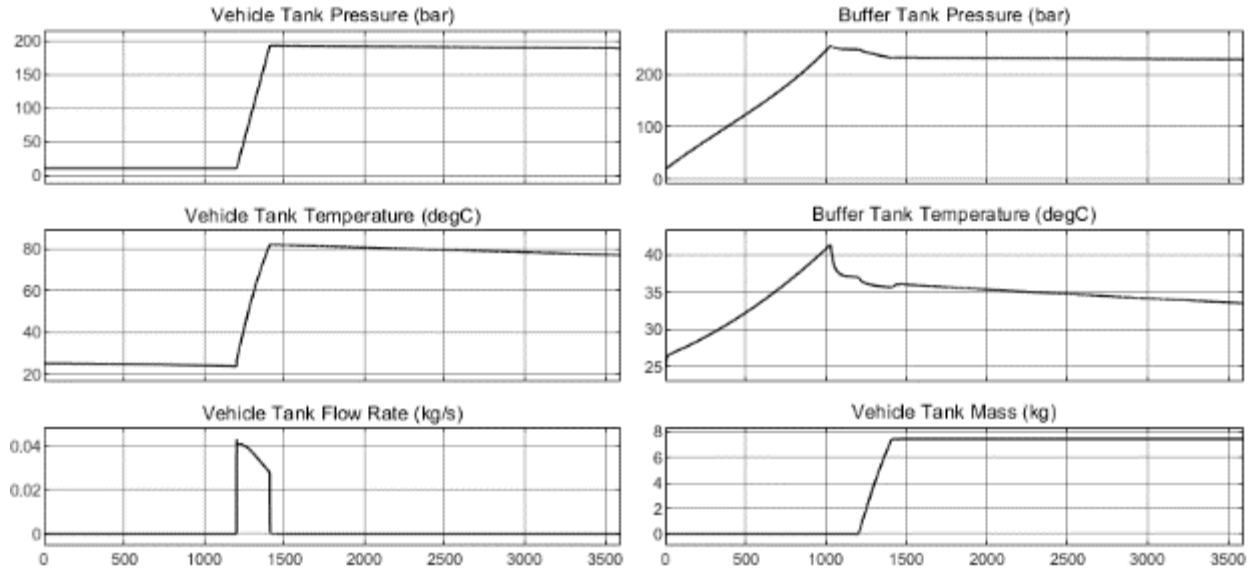
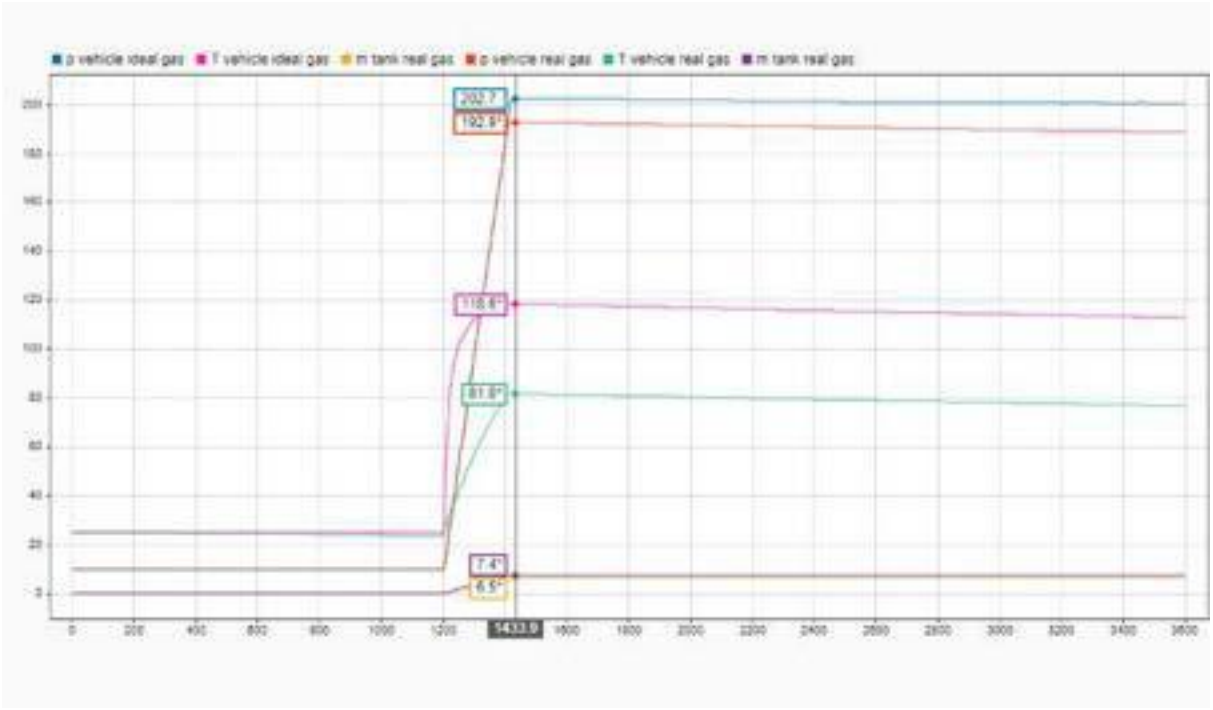


Fig. 2. Simulation Results for Real Gas Assumptions

Fig. 3. Compare the Simulation Results for Ideal and Real Gas Assumptions



The compare of the simulation results for ideal gas and the real gas assumptions are shown in Figure 3. The NGV cylinder final pressure is 202.7 bar for ideal gas and 192,9 bar for real gas. The temperature of NGV cylinder rises 118.6^0 C for ideal gas and 81.8^0 C for real gas. Total mass of the CNG in NGV cylinder is 6.5 kg for ideal gas and 7.4 kg for real gas.

V. Conclusion

The Compressed Natural Gas (CNG) station model was created by using the Matlab/Simulink/Simscape media. Since, CNG is stored in high pressure cylinder on the vehicles, natural gas must be pressurized then charge on the vehicles tanks in a required very short time interval. It is generally required to make fast filling process under 300s. For fast filling process, buffer tanks are used. In the simulations, both ideal gas approach and real gas properties are employed. Comparing both gases approach, it is observed that Natural Gas Vehicle (NGV) cylinder's temperature increases in an acceptable range for real gas properties, however, higher temperature increases observed for ideal gas. Meanwhile, it is also observed that the temperature rises caused to less mass filling in CNG cylinder.

To prevent this and to get more mass in cylinder, the buffer tanks can changed with multi line storage system (cascade system).

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