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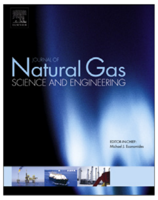

Mathematical modeling of fast filling process at CNG refueling stations considering connecting pipes

Javad Khadem [a], Morteza Saadat-Targhi [a, *], Mahmood Farzaneh-Gord [b]

[a] The Faculty of Mechanical Engineering, University of Birjand, Birjand, Iran
[b] The Faculty of Mechanical Engineering, Shahrood University of Technology, Shahrood, Iran

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ABSTRACT

One of the most important parameter in design of a compressed natural gas refueling station is detailed modeling of fast filling process. In this work, a new mathematical model was developed to analyze the fast filling process at compressed natural gas refueling stations. This new model is unique because connecting pipes between reservoir tanks and on-board vehicle cylinder also were taken into account. To model the process, the equation of state, continuity, momentum and energy equations have been solved for different parts of the system. The results have been validated against the experimental data to investigate effects of connecting pipes. The mass flow rate numerical values are in good agreement with the experimental values. The study carried out for both cascade and buffer storage systems. Variations of pressure and Mach number at different parts of the system, effects of the initial reservoir tank temperature on natural gas vehicle in-cylinder pressure and temperature are presented. The results show that pressure loss through pipes is very important and should be considered. Mass flow rate between reservoir tank and on-board cylinder is nearly constant (as the flow is chocked) during filling. Temperature growth rate at the beginning of the process is higher for the buffer system. It is also found that there is a temperature rise around 85 K for ideal gas model.

1. Introduction

Problems arising from the use of liquid fuels such as environmental pollution and high cost of production on the one hand and the low price of natural gas make tend to use natural gas as a vehicle fuel. Compressed Natural gas (CNG) usually used as clean fuel for vehicles. CNG is stored in high-pressure tanks on the vehicle (190–250 bar). Natural gas is consists mostly of methane, which was first used as a transportation fuel in 1930. In recent years the use of fuel gas (CNG and Hydrogen) as the main fuel has increased in the world. Natural gas vehicles (NGVs) connect to the high-pressure reservoir tanks at refueling stations during filling process. One of the most problems with NGVs refueling stations is the time to refuel an NGV (filling time). This filling (<5 min) is referred as a fast fill. The second and main problem using this type of fuel is high operating costs at the refueling stations. Thus, a simulation to optimize the refueling process is very important. The basic research has been done on the process of filling, which have been identified possibility of increasing the efficiency of the refueling stations, (Farzaneh-Gord et al., 2011; Banapurmath et al., 2013).

Reservoir tanks in a cascade storage system are divided into high, medium and low pressures (Fig. 1). In a cascade storage system, reservoir tanks are filled on a priority identified by an algorithm. Based on the algorithm, the on-board NGV cylinder is switched from lower pressure reservoir to higher one, when the mass flow rate drops to certain limit. In a buffer storage system, reservoir tanks are maintained at same pressure during all time (Fig. 2).

Kountz (Kountz, 1994) who was pioneer in modeling fast filling process, presented a simple thermodynamic model to modeling the fast filling process. The effects of heat transfer from the on-board NGV cylinder are considered in his modeling. The model was simple with only considering one reservoir tank and on-board NGV cylinder. Kountz et al. (Kountz et al., 1997, 1998a, 1998b, 1998c), have also used a dispenser control process. Farzaneh-Gord et al. (Farzaneh-Gord, 2008; Farzaneh-Gord et al., 2007) modeled the process of fast filling for the buffer storage system in a CNG refueling station. They studied effects of initial reservoir tanks pressure and ambient condition on final on-board NGV cylinder temperature, pressure and filling time. Likewise all studies in the literature,

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* Corresponding author.
E-mail address: Msaadat.Targhi@yahoo.com (M. Saadat-Targhi).

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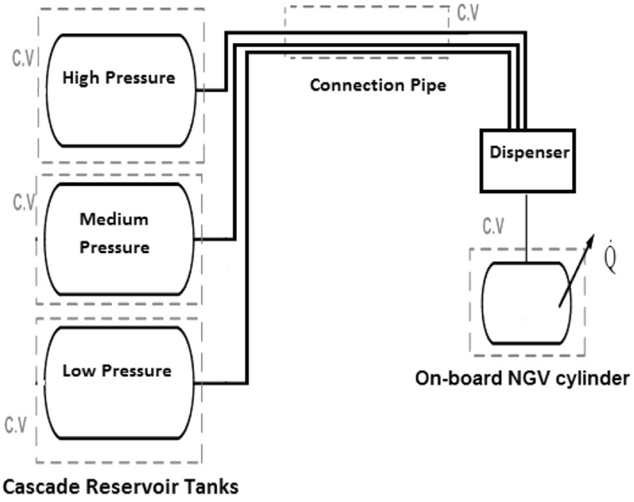

Fig. 1. A simple cascade storage system.

their model based on two cylinders (reservoir tank and on-board NGV cylinder) without considering pipe, valves and dispenser. Using previous models, Farzaneh-Gord et al. (Farzaneh-Gord et al., 2008) presented a thermodynamic analysis of cascade storage bank CNG refueling station. They showed that initial conditions and ambient temperature have an enormous effect on final on-board NGV cylinder conditions and filling mass and time. Their results showed that there was a temperature rise of at least 40 K through the fast filling process for real gas. Farzaneh-Gord et al. (Farzaneh-Gord et al., 2011; Deymi-Dashtebayaz et al., 2012) developed a theoretical analysis based on real gas assumptions to study effects of storage system type on performance of CNG refueling stations. The results present both of storage systems have advantages over the other. They found that filling time in the buffer storage system is about 66% less than cascade storage system. The most advantage of the cascade storage system over the buffer is 50% less entropy generation. Their model based on two cylinders similar to the former ones. Farzaneh-Gord et al. (Farzaneh-Gord et al., 2012a) repeated their analysis for hydrogen refueling stations. Farzaneh-Gord et al. (Farzaneh-Gord and Deymi-Dashtebayaz, 2013; Farzaneh-Gord et al., 2012b) optimized CNG refueling station reservoir tank pressure based on thermodynamic analysis. The time of filling and the entropy generation have opposite trends and as entropy generation decreases, the filling time increases. The results show that the optimized non-dimensional low and medium pressure-reservoir tank pressures are found to be as 0.24 and 0.58 respectively in thermodynamic point of view. Farzaneh-Gord et al. (Farzaneh-Gord et al., 2014) studied the effects of natural gas compositions on performance of refueling stations for buffer storage system. They found that the filling time for Pars natural gas type (with about 87% methane) is about 15 s less than Khangiran natural gas (with about 98% methane). They found that the natural gas composition has a significant influence on the fast filling process and the on-board NGV cylinder conditions at the end of process. An equation has been constructed for foretelling heat transfer rate between in-cylinder flow and inner surface cylinder wall, based on a numerical simulation by Deymi-Dashtebayaz et al. (Deymi-Dashtebayaz et al., 2014). Afterward, a thermodynamic method has been developed for foretelling pressure and temperature variations inside the cylinder and transient wall temperature during the refueling. The results showed that a major portion of heat dissipation from the in-cylinder flow is reserved in the cylinder wall. The best operating condition for attaining either the minimum energy consumption in compressors and coolers or the maximum final accumulated mass of gas within cylinders was determined using particle swarm optimization algorithm by Khamforoush et al. (Khamforoush et al., 2014). The optimum pressure arrangements were 4.0–16.0–20.5 MPa for three cascade storage system.

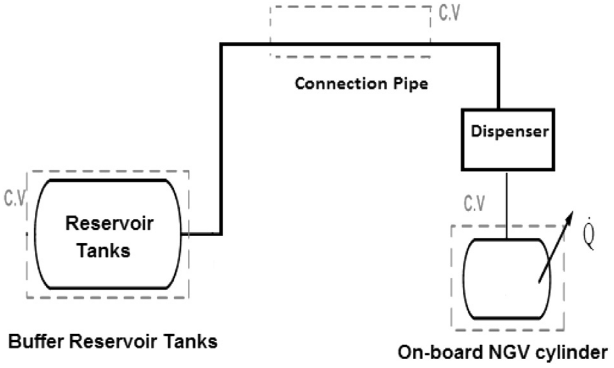

Fig. 2. A simple buffer storage system.

Having an accurate model for fast filling process in CNG refueling station is of paramount importance. There is a need to improve the initial modeling to achieve more accurate results. The aim of the current work is to present a more detailed modeling of fast filling process occurred in a CNG refueling station. In this study, fast filling process has been modeled completely. Unlike the previous studies in which connection pipes and nozzle have been modeled as an orifice, the connecting pipes have been added to the model. Nozzle as one of the most important parts of CNG refueling equipment is also considered. The nozzle is modeled as a variation in pipes cross sectional area (convergent nozzle). The effect of physical and geometric properties such as: inside diameter, length of pipes and friction factor could not be examined by considering orifice as connection type between the reservoir and the on-board cylinder. These parameters have been considered in the present work for first time. The results of the model with connecting pipes have been validated against the experimental data and also compared with the results of a previous work to investigate the effect of connecting pipes (Farzaneh-Gord et al., 2011).

2. Mathematical model

The thermodynamic model carried out here, involves the transient flow of an ideal gas from high-pressure reservoir tanks to an on-board NGV cylinder (Figs. 1 and 2) through the pipe and convergent nozzle (Fig. 3). Assumptions made in the model are:

- Temperature and pressure are assumed to be uniform in the reservoir tanks and on-board NGV cylinder.
- Stagnant conditions are assumed in the reservoir tanks.
- The ideal gas law is assumed.
- The flow is treated as one-dimensional.
- The flow is supposed to be adiabatic through the pipe because the process is very fast and residence time is very short.
- The flow is supposed to be isentropic through the convergent nozzle.
- Transient process is a quasi-steady process.
- The friction loss through the nozzle is small enough to be ignored because the length of the nozzle (about 0.05 m) is very small compared to the pipe length (about 50 m).

The detailed modeling carried out in this study is presented in following sections for each part of the system:

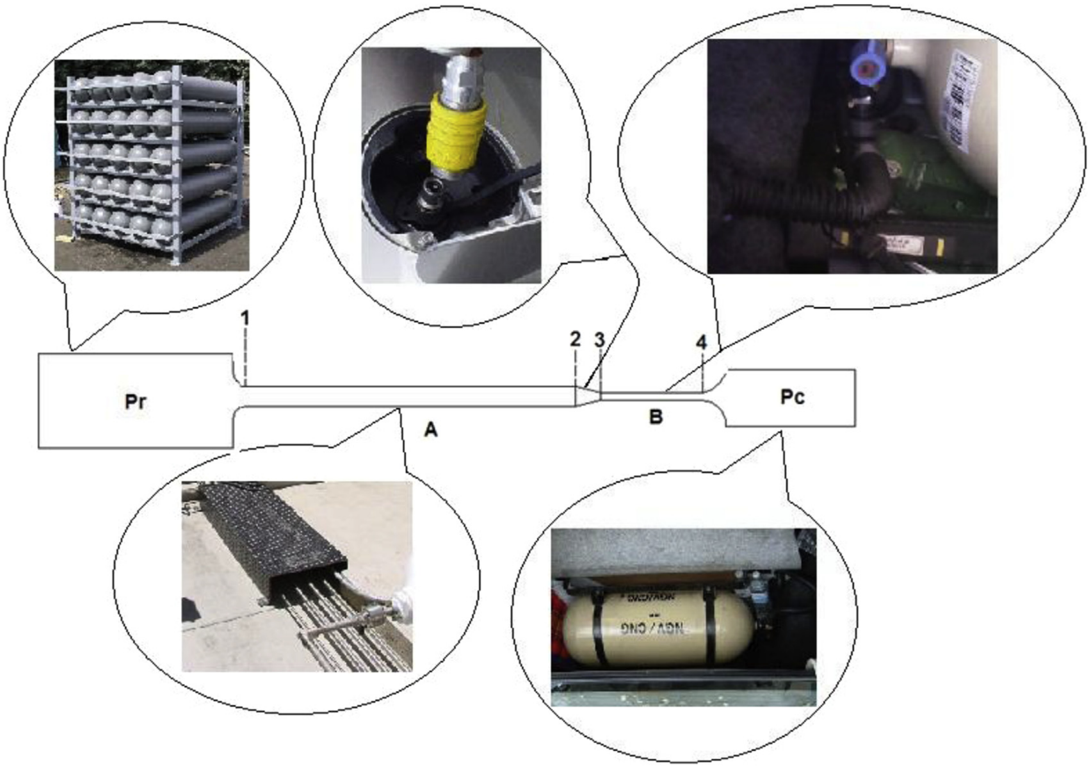

Fig. 3. A schematic diagram of the problem under investigation.

2.1. Connection pipe

The natural gas flow between reservoir tanks and on-board NGV cylinder is modeled as a Fanno flow. Flow through the nozzle is assumed isentropic with variable cross section area. Fanno flow refers to adiabatic flow through a constant area pipe where the effect of frictional pressure drop is considered. To calculate the mass flow rate of gas, continuity, momentum and energy equations and equation of state must be solved for pipe A and B in Fig. 3.

The governing equations (Continuity, momentum, energy and state equation) for pipe flow are as follows, (Oosthuizen and Carscallen, 1997):

$$\frac{d(\rho V)}{dx} = 0 \tag{1}$$

$$\frac{d(\rho VV)}{dx} + \frac{dP}{dx} + \frac{f}{2d}\rho V^2 = 0 \tag{2}$$

$$\frac{d}{dx}\left(\rho V\left(h + \frac{V^2}{2}\right)\right) = 0 \tag{3}$$

$$P = \rho \frac{R}{M} T \tag{4}$$

where, ρ, V, P, f, d, h, R, M and T are density, velocity, pressure, Fanning friction factor, diameter of pipe, enthalpy, gas constant, molecular weight and temperature, respectively. Introducing Mach number definition and natural gas mass flow rate equation could be obtained by Equation (6):

$$M_a = \frac{V}{\sqrt{kRT}} \tag{5}$$

$$\dot{m} = \frac{P}{RT} A M_a \sqrt{kRT} \tag{6}$$

where M_a and A are Mach number and cross section of pipe, respectively. By these definitions, Equations (1)–(4) yield:

$$\frac{fk}{2d}dx = \frac{1 - M_a^2}{M_a^2\left(1 + ((k-1)/2)M_a^2\right)} \frac{dM_a}{M_a} \tag{7}$$

$$\frac{dP}{P} = -\frac{1 + (k+1)M_a^2}{1 + ((k-1)/2)M_a^2} \frac{dM_a}{M_a} \tag{8}$$

$$\frac{dT}{T} = -\frac{(k-1)M_a dM_a}{1 + ((k-1)/2)M_a^2} \tag{9}$$

2.2. On-board NGV cylinder

Applying the mass conservation equation to the control volume (the on-board NGV cylinder):

$$\frac{dm_c}{dt} = \dot{m}_i \tag{10}$$

That ṁ is inlet mass flow rate, described in the previous section. The general form of the first law of thermodynamics for the control volume yields:

$$\dot{Q}_{cv}+\sum\dot{m}_i\left(h_i+V_i^2\big/2+gz_i\right)=\sum\dot{m}_e\left(h_e+V_e^2\big/2+gz_e\right)+d/dt\left[m\left(u+V^2\big/2+gz\right)\right]_{cv}+\dot{W}_{cv} \tag{11}$$

The change in kinetic and potential energy and the work term could be neglected as there is only one inlet, yields:

$$\frac{dU_c}{dt}=\dot{Q}_{cv}+\dot{m}_i\left(h_i+\frac{V_i^2}{2}\right) \tag{12}$$

The above equation could be more simplified by replacing enthalpy of the reservoir tanks:

$$\frac{dU_c}{dt}=\dot{Q}_{cv}+\dot{m}_i(h_r) \tag{13}$$

To simplify, the heat transfer of on-board NGV cylinder to environment is negligible. Finally, the first law of thermodynamics could be written as for the on-board NGV cylinder:

$$m_c\frac{du_c}{dt}+u_c\frac{dm_c}{dt}=\dot{m}_ih_r \tag{14}$$

For an ideal gas behavior, internal energy and enthalpy are only temperature dependent: $h=c_pT$ and $u=c_vT$, where c_p and c_v are constant pressure specific heats and constant volume specific heats, respectively.

2.3. Numerical procedure

The set of Equations (4), (6)–(10) and (14) form the fast filling modeling. A numerical procedure has to be followed to solve these equations. Reservoir tanks pressure and temperature are assumed constant and known. Initial pressure and temperature of the on-board NGV cylinder are also known. Mathematical modeling is continued for a small time step ($\Delta t=0.01$).

The pipe flow modeling begins with identifying the critical pressure ($P_{critical}$) which causing flow choked at the end of pipe B, ($M_{a4}=1$) by using Equations (7)–(9). Other thermodynamic properties at various positions of pipe A and B are detected by using these equations in each time step. For pressures below the critical pressure ($P_4\le P_{critical}$), flow is choked and gas mass flow rate is constant and detected by using Equation (6). For pressures bigger than the critical pressure ($P_4>P_{critical}$), flow is not choked and the mass flow rate of gas for different pressures can be calculated by a trial and error procedure. P_4 is calculated in the previous time step (calculated pressure). An amount is estimated for M_{a4} below 1. Then, the P_4 will be achieved by using Equations (7)–(9), (estimated pressure). Calculated pressure is compared with the estimated pressure, if it has a good accuracy, the answer is obvious, otherwise the initial guess (M_{a4}) is varied and this process continues until the final answer is determined.

After determining the mass flow rate in a time step, differential Equations (10) and (14) are solved to achieve charged mass of the on-board NGV cylinder and internal energy in the new time step. Given volume of the on-board NGV cylinder and mass, specific volume (v) can be calculated. Now, other thermodynamics properties should be possible to calculate by knowing equation of state for ideal gas in new time step. This procedure continues until the on-board NGV cylinder pressure reaches to its final value. The flow chart of numerical procedure is shown in Fig. 4.

3. Results and discussion

3.1. Validation and comparison

In this section, the numerical values has been compared with experimental data of George, (George and Mayeaux, 2014) and also with computed results of the previous works (Farzaneh-Gord et al., 2011, 2007, 2008; Kountz, 1994; Deymi-Dashtebayaz et al., 2012; Farzaneh-Gord et al., 2012a; Farzaneh-Gord and Deymi-Dashtebayaz, 2013; Farzaneh-Gord et al., 2012b, 2014). The cylinder volume is 52 litters, initial pressure of on-board NGV cylinder is 72 bar and the other information about the geometric properties of pipes and reservoir tanks are provided in Table 1. In Fig. 5, the reservoir tanks pressure variation during filling process is presented for the experiment and numerical method. Fueling has started after 24 s and has ended after 36 s from start time. It is evident that there is a cascade storage system with two reservoir tanks 1 and 2. The initial pressure is equal for reservoir tanks 1 and 2, 251 bar. Fast filling process has started with draining the reservoir tank 1 and after 26 s, has switched to tank 2. It can be observed that over time, the reservoir pressure is reduced. In the modeling the reservoir tanks pressure are constant and equal the average pressure at the beginning and the end of the process.

The mass flow rate was measured throughout the experiment (George and Mayeaux, 2014). It varied between 0.29 and 0.0 kg/s. When the mass flow rate drops to 0.04 kg/s, the on-board NGV cylinder is switched to reservoir tanks 2 or stopped filling process. The mass flow rate of gas vs. time curve is shown in Fig. 6. It could be realized that, the simulation result of mass flow rate in present work is good agreement with the experimental values. The deviation mainly may be due to the mentioned assumptions. At the starting time of filling, mass flow rates are not constant because the initial pressure in vehicle cylinder is higher than the critical pressure and flow is not chocked. As it is evident, the decreasing trend of experimental values is almost linear and it could be also seen in result of present work, while the decreasing trend of mass flow for previous work is Exponential. Also, the results of the present work have a good prediction for filling time and have only 2 s differences from measured values. It is about 10 s for previous works (Farzaneh-Gord et al., 2011, 2007, 2008; Kountz, 1994; Deymi-Dashtebayaz et al., 2012; Farzaneh-Gord et al., 2012a; Farzaneh-Gord and Deymi-Dashtebayaz, 2013; Farzaneh-Gord et al., 2012b, 2014). It should be noted that, in previous works (Farzaneh-Gord et al., 2011, 2007, 2008; Kountz, 1994; Deymi-Dashtebayaz et al., 2012; Farzaneh-Gord et al., 2012a; Farzaneh-Gord and Deymi-Dashtebayaz, 2013; Farzaneh-Gord et al., 2012b, 2014c, to determine the mass flow rate between the reservoir tanks and on-board NGV cylinder, the ideal mass flow rate is multiplied by a discharge coefficient. The discharge coefficient is usually selected using matching experimental and numerical values. The ideal mass flow rate is calculated by assuming an isentropic process for natural gas flow between the reservoir tanks and the on-board NGV cylinder.

The comparison of on-board NGV cylinder pressure during filling process for experiment, present and previous works are presented in Fig. 7. Some differences are discovered in this figure. The results of the present work and previous works are higher than experiment work during the filling process. It may be caused by the assumption of the heat transfer of on-board NGV cylinder to environment is negligible and ideal gas model. Although the real gas model has been used in previous works, but the results of present work is more accurate. The reason of accurate prediction of mass flow rate is due to model the connecting pipes. The modeling of connecting pipes in present work cause the better dynamic pressure profile than the previous works (Farzaneh-Gord et al., 2011, 2007, 2008; Kountz, 1994; Deymi-Dashtebayaz et al., 2012;

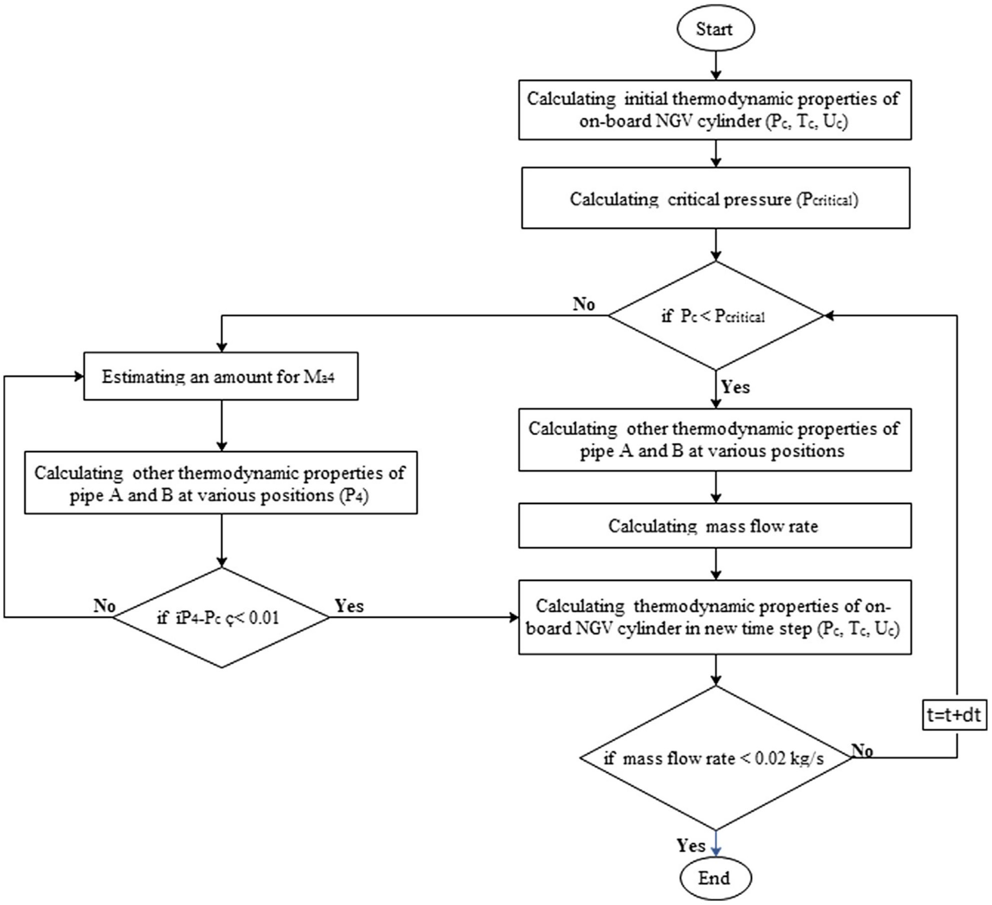

Fig. 4. Flow chart of numerical procedure.

Farzaneh-Gord et al., 2012a; Farzaneh-Gord and Deymi-Dashtebayaz, 2013; Farzaneh-Gord et al., 2012b, 2014).

3.2. Simulation results

CNG is mainly composed of methane, so in this work CNG assumed pure methane. The model is used to predict the dynamic temperature and pressure variation during fast filling process for buffer and cascade storage systems. Information about CNG refueling station and NGV is presented in Table 1. This information is obtained from a typical CNG refueling station (Baghdar CNG station No.1043, Mashhad, Iran). The reservoir condition assumed to be unchanged. The results presented in this work are for the cascade storage system with three levels pressure as 100, 160 and 220 bar, for the buffer storage system it is assumed to be 220 bar. These results are also presented for the case when the initial temperature was kept constant at 293 K.

Table 1
Some information about CNG refueling station and NGV on-board cylinder.

Inside diameter of pipe A	0.007 m
Inside diameter of pipe B	0.003 m
Length of pipe A	50 m
Length of pipe B	1 m
Mean friction factor	0.01
Storage capacity of on-board NGV cylinder	101 l
Storage capacity of station	5760 l
Priority panel	3 line
Reservoir tanks quantity	48

Fig. 8 shows the pressure variation through the fast filling process for buffer and cascade storage system at various positions. It is clear that filling time is smaller for buffer storage system comparing the cascade storage system. This is mainly due much higher pressure difference between reservoirs and on-board NGV cylinder for buffer system. Note that the filling time (target pressure is 200 bar)

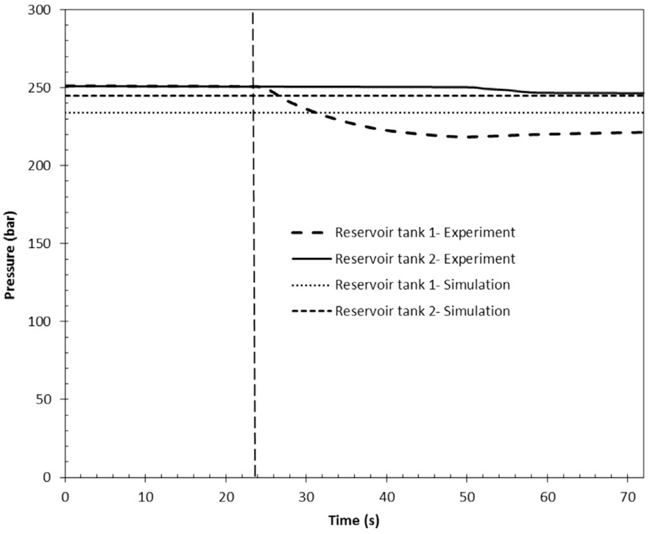

Fig. 5. Pressure variations of reservoir tanks for experiment and simulation processes.

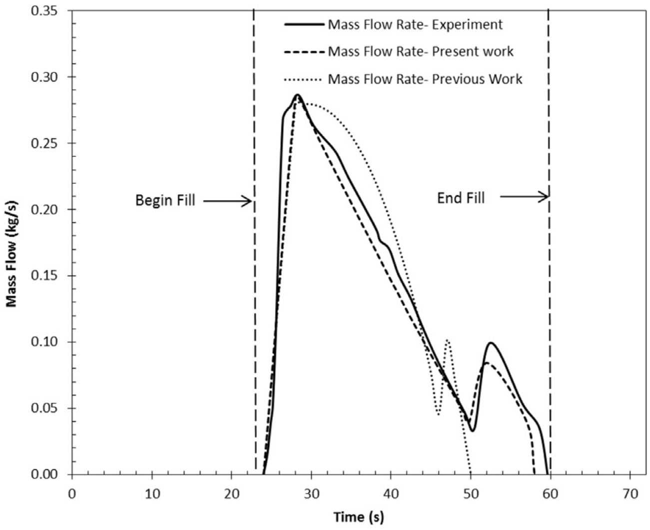

Fig. 6. Mass flow rate variations for experiment and simulation processes.

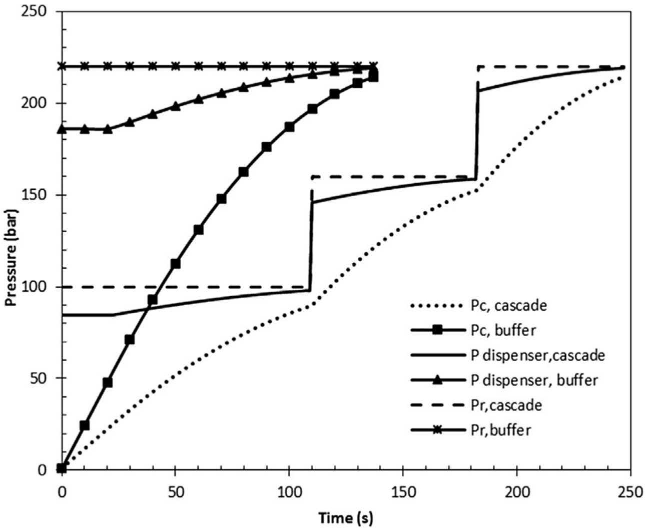

Fig. 8. Pressure variations for cascade and buffer storage systems at various positions.

for the buffer system is about 44% less than in the cascade system. Usually dispensers have a pressure sensor. When the valve installed before the dispenser is closed, NGV cylinder pressure is determined by this sensor. The pressure sensor is used as a control system for determining finishing point of the refueling process. So pressure in the dispenser is important. The results of dispenser pressure are presented in the figure, too.

Mass flow rate of gas is certainly one of the most important parameters in the process of fast filling. Fig. 9 shows the mass flow rate of the gas for cascade and buffer storage systems. Based on dispenser algorithm, the on-board NGV cylinder is switched from lower pressure reservoir to higher one, when the mass flow rate drops to certain limit (usually 0.02 kg/s). This is observed in Fig. 9. At the starting time of filling, mass flow rates are nearly constant because flow is chocked for both buffer and cascade storage system. According the figure, the mass flow rate of gas profile in the cascade storage system is divided into three separate parts. The profile for buffer storage system is similar to one part of cascade profile. One of the advantages of the present work is more accurate prediction for mass flow rate than the previous works. As was stated in Validation and comparison section, the decreasing trend of mass flow rate during the filling process is Linear. In another experimental research related to hydrogen refueling stations, the decreasing trend has been mentioned linear too (Monde et al., 2012).

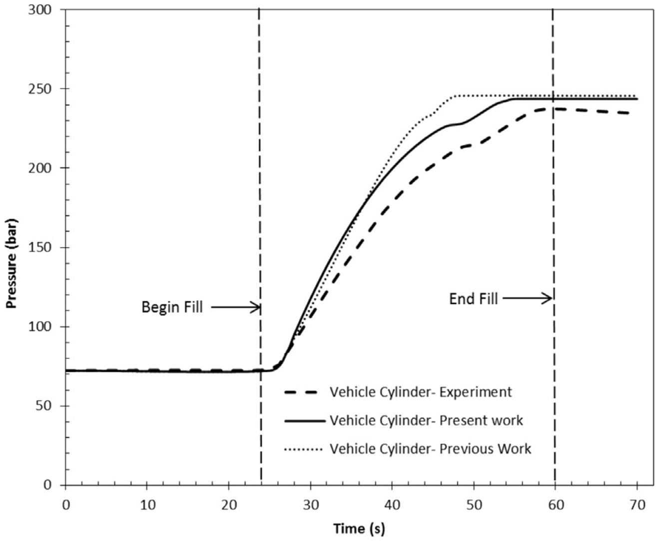

Fig. 7. Pressure variations of NGV cylinder for experiment and simulation processes.

Temperature versus time curve is shown in Fig. 10 for both buffer and cascaded storage systems. As is shown in this figure growth rate for temperature at the beginning of the process is higher for the buffer storage system. The same trend in the temperature profile has been seen in previse studies (Farzaneh-Gord et al., 2011, 2007, 2008; Kountz, 1994; Deymi-Dashtebayaz et al., 2012; Farzaneh-Gord et al., 2012a; Farzaneh-Gord and Deymi-Dashtebayaz, 2013; Farzaneh-Gord et al., 2012b, 2014). The final temperature of the actual conditions may be less than the modeling value. The use of the ideal gas model and the lack of Joule-Thompson cooling effect are the most important factor for this different. Both storage types show a rapid increase in temperature at early time of refueling, while the temperature remains constant during the end of the filling process. The final temperature is almost identical for both storage systems. It should be pointed out that final temperature is very important, as it is associated with the in-cylinder mass. The filled mass is higher for the case where the final in-cylinder temperature is lower.

In Fig. 11, the on-board NGV cylinder mass variation during fast filling process is presented. The on-board NGV cylinder mass is directly related to the final in-cylinder temperature. It can be seen that at the end of the filling the in-cylinder mass is reached to about 11 kg for both storage systems. It could be realized that filling time for buffer storage system is much lower than the cascade storage system. After filling process the on-board NGV cylinder pressure would be decreased as the ambient temperature most likely is higher that final in-cylinder gas temperature. Therefore, the final in-cylinder pressure cannot be a good measure for estimating the charged mass. The increasing trend of on-board NGV cylinder mass during the filling process is similar to the pressure variation through the fast filling process for the on-board NGV cylinder. This similarity has been seen in previous works (Farzaneh-Gord et al., 2011, 2007, 2008; Kountz, 1994; Deymi-Dashtebayaz et al., 2012; Farzaneh-Gord et al., 2012a; Farzaneh-Gord and Deymi-Dashtebayaz, 2013; Farzaneh-Gord et al., 2012b, 2014).

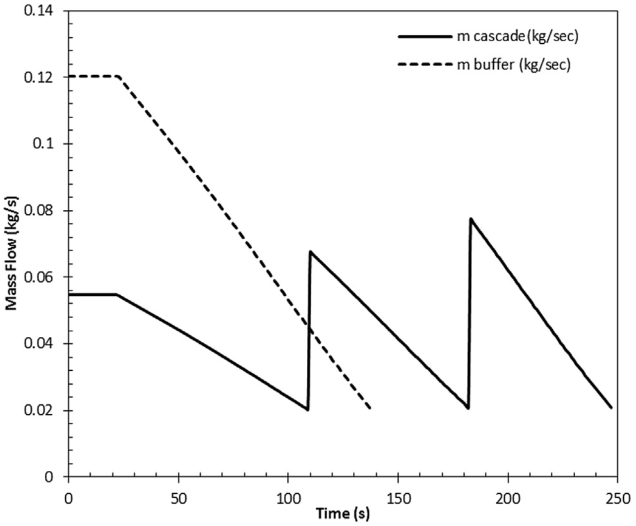

Fig. 9. Natural gas mass flow rate variation for cascade and buffer storage systems.

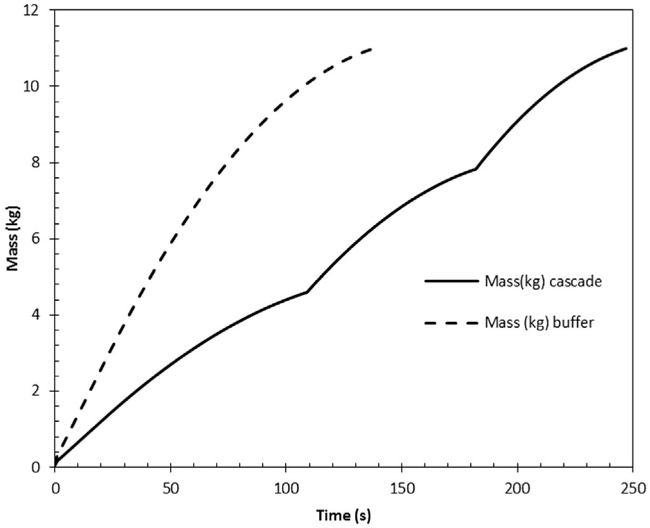

Fig. 11. The on-board NGV cylinder mass variation during the filling process.

Variations of pressure at various positions of the system are shown in Fig. 12. Pressure drops in the system can be observed through these results. As it could be realized, pressure variations have been calculated for four different locations: reservoir tanks, before nozzle, after nozzle and the on-board NGV cylinder. While in the previous works (Farzaneh-Gord et al., 2011, 2007, 2008; Kountz, 1994; Deymi-Dashtebayaz et al., 2012; Farzaneh-Gord et al., 2012a; Farzaneh-Gord and Deymi-Dashtebayaz, 2013; Farzaneh-Gord et al., 2012b, 2014), pressure variations could only be presented for 2 different locations: reservoir tanks and the on-board NGV cylinder. This upgraded model (present work) could be useful for designing the dispenser algorithm. It should be noted that the results are for the cascade and buffer storage systems when initial temperature was kept constant at 293 K. The pressure drop in pipes and nozzle are higher at the beginning of refueling process. Pressure remains constant at positions P_2 and P_3 at early time of the refueling process and then increases. This is due to constant Mach number at these positions (P_2 and P_3) at the early time and subsonic condition as time increases. At the beginning of the process of refueling for both storage systems, the slope of rising pressure (P_c) is constant because flow in pipe is chocked (Fig. 9). These could be seen in Fig. 13.

Variations of Mach number at various positions of the system are also very important. The Variations of Mach number for the cascade and buffer storage system is shown in Fig. 13. As it can be seen, the highest Mach number becomes apparent at the beginning of the point 4 for both. Mach number is always less than or equal one, therefor gas flow is always subsonic flow and shock waves are not formed in the pipes. Undoubtedly, this high Mach number is one of the important factors for temperature rise. It should be noted that the Mach number have not been presented in the previous works (Farzaneh-Gord et al., 2011, 2007, 2008; Kountz, 1994; Deymi-Dashtebayaz et al., 2012; Farzaneh-Gord et al., 2012a; Farzaneh-Gord and Deymi-Dashtebayaz, 2013; Farzaneh-Gord et al., 2012b, 2014).

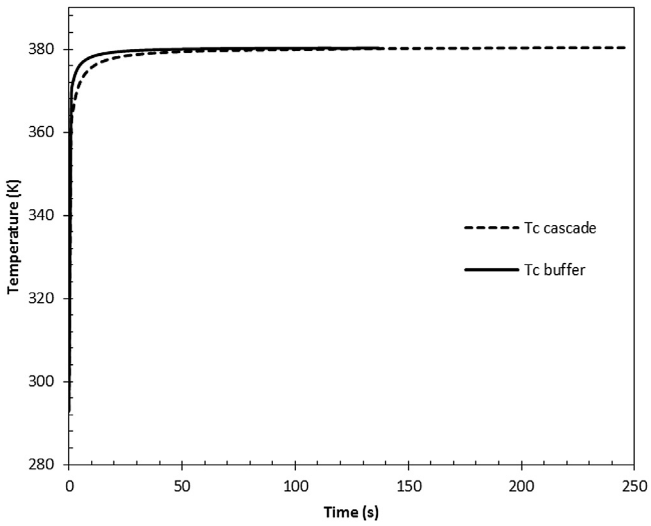

Fig. 10. Temperature developments in the on-board NGV cylinder.

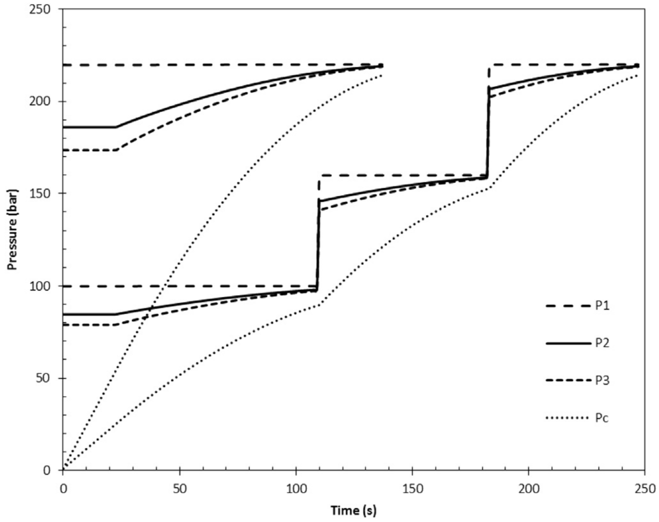

Fig. 12. Pressure variations at various positions of the cascade and buffer storage systems.

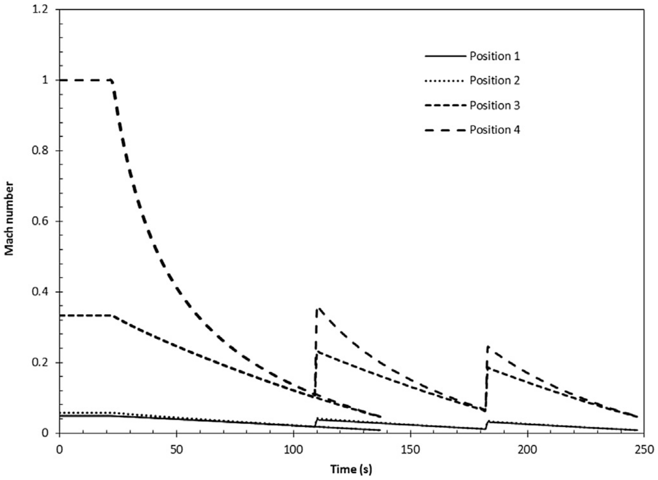

Fig. 13. Variations of Mach number at various positions of the cascade and buffer storage systems.

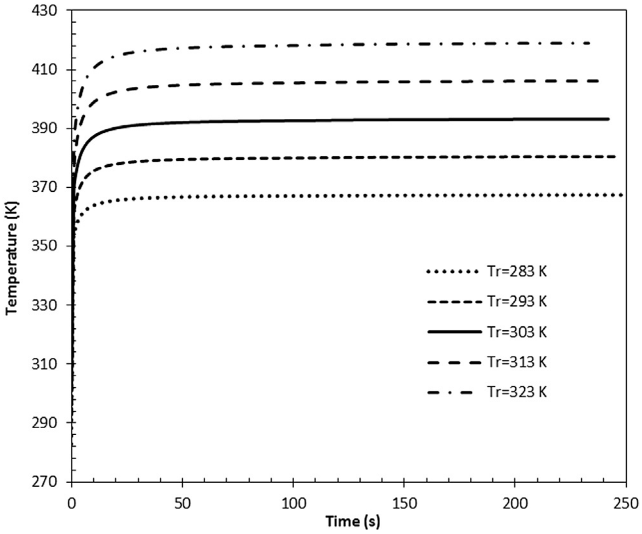

Fig. 15. Effect of initial reservoir tank temperature on on-board NGV cylinder temperature for the cascade storage system.

Fig. 14 shows the effects of the initial reservoir tank temperature on on-board NGV cylinder pressure for cascade and buffer storage systems. It could be realized the reservoir temperature has an effect on pressure variation within the onboard cylinder. When the compressor is off, the initial reservoir tank temperature is equal to the ambient temperature and when it is on, the initial reservoir tank temperature is equal to compressor outlet temperature. Since the compressor outlet temperature is always greater than the ambient temperature, the initial reservoir tank temperature is always higher than the ambient temperature. Outlet temperature of the compressor is influenced by ambient temperature because there is an air cooler at the compressor output. So the reservoir tank temperature is always influenced by ambient temperature. As it can be seen, by increasing the initial reservoir tank temperature from 283 K to 323 K, filling time decreased to 20 s for cascade and 10 s for buffer storage systems.

Fig. 15 shows the effects of the initial reservoir tank temperature on on-board NGV cylinder temperature for cascade storage system. As shown in this figure, the on-board NGV cylinder gas temperature rises sharply during early time of filling. As previously presented, reservoir tank temperature is always influenced by ambient temperature. So the final temperature of on-board NGV cylinder is affected by ambient temperature. Final temperature of on-board NGV cylinder is an important parameter in safety issues. As it seen in this figure, by increasing the initial reservoir tank temperature from 283 K to 323 K (40 K), final on-board NGV temperature cylinder increases 60 K for cascade storage system. The similar results could be found in previous works (Farzaneh-Gord et al., 2011, 2007, 2008; Kountz, 1994; Deymi-Dashtebayaz et al., 2012; Farzaneh-Gord et al., 2012a; Farzaneh-Gord and Deymi-Dashtebayaz, 2013; Farzaneh-Gord et al., 2012b, 2014).

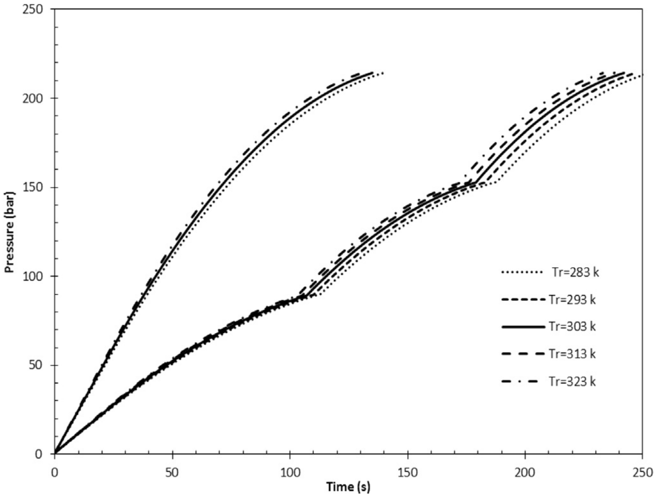

Fig. 14. Effects of initial reservoir tank temperature on on-board NGV cylinder pressure for the cascade storage system.

4. Conclusion

In this work, a highly accurate mathematical model is developed to evaluate the fast filling process at CNG refueling stations. To model the process, the equation of state, continuity, momentum and energy equations is solved for different parts of the station. A numerical procedure has been developed to calculate mass flow rate of gas in the connection pipe. In all previous studies, CNG refueling station modeled base on only two reservoir tanks without considering the connection pipe. This new model could predict thermodynamic conditions of NG in all parts of the CNG refueling station as well. The numerical results have been validated against the experimental data and also compared with the results of a previous computed work to study the effect of connecting pipes. The simulation result of mass flow rate is good agreement with the experimental value. Variations of pressure and Mach number at varicose positions of the system, effects of initial reservoir tank temperature on on-board NGV cylinder pressure and temperature are presented for cascade and buffer storage systems. The results show that pressure loss in the fast filling process is very important and should be considered. Mass flow rate of gas is certainly one of the most important parameters in the process of fast filling. At the start of process, mass flow rates are nearly constant because flow is chocked for both buffer and cascade storage system. Growth rate for temperature at the beginning of the process is higher for the buffer system. The results show that there is a temperature rise of about 85 K for this process.

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Nomenclature

A	area, (m^2)
c_p	constant pressure specific heats (kJ/kg K)
c_v	constant volume specific heats (kJ/kg K)
d	diameter (mm)
f	fanning friction factor
g	gravitational acceleration, (m/s^2)
h	enthalpy, (kJ/kg)
k	isentropic expansion factor
L	length (m)
$\dot{m}$	mass flow rate, (kg/s)
M	molecular weight, (kg/kmol)
M_a	Mach number
P	pressure, (bar or kPa)
$\dot{Q}$	heat transfer rate, (kW)
R	gas constant (J/mol K)
T	temperature, (K or °C)
u	internal energy, (kJ/kg)
t	time, (s)
V	velocity (m/s)
V	volume, (m^3)
W	actual work, (kJ/kg)
$\dot{W}$	actual work rate, (kW)
z	height, (m)
ρ	density, (kg/m^3)

Subscript

A	pipe A
B	pipe B
r	reservoir tank
c	on-board NGV cylinder
cv	control volume
i	inlet condition
1	point 1
2	point 2
3	point 3
4	point 4

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