IMPROVEMENT OF MC METHOD IN SAE J2601 HYDROGEN REFUELLING PROTOCOL USING DUAL-ZONE DUAL-TEMPERATURE MODEL

Luo, H.[1,2,3], Xiao, J.S.[1,2], Bénard, P.[2], Chahine, R.[2], Tong, L.[4], Yuan, Y.P.[4], Yang, T.Q.[1] and Yao, C.L.[3]***

[1]School of Automotive Engineering, Wuhan University of Technology, Hubei, 430070, China, Hao.Luo@whut.edu.cn, Jinsheng.Xiao@whut.edu.cn, tqyang@whut.edu.cn
[2]Hydrogen Research Institute, Université du Québec à Trois-Rivières, QC, G8Z 4M3, Canada, Pierre.Benard@uqtr.ca, Richard.Chahine@uqtr.ca
[3]School of Mechanical and Electrical Engineering, Wuhan Business University, Hubei, 430056, China, 670070298@qq.com
[4]School of Transportation and Logistics Engineering, Wuhan University of Technology, Hubei, 430070, China, tongliang2@whut.edu.cn, ypyuan@whut.edu.cn

ABSTRACT

The MC method refuelling protocol in SAE J2601 has been published by the Society of Automotive Engineers (SAE) in order to safely and quickly refuel hydrogen vehicles. For the calculation method of the pressure target to control the refuelling stop, we introduced a dual-zone dual-temperature model that distinguishes the hydrogen temperature in the tank from the wall temperature to replace the dual-zone single-temperature model of the original MC method. The total amount of heat transferred by convection between hydrogen and the inner tank wall during the filling process was expressed as an equation of final hydrogen temperature, final wall temperature, final refuelling time, tank inner surface area and the correction factor. The correction factor equations were determined by fitting simulation data from the 0D1D model where hydrogen inside the tank is lumped parameter model (0D), and the tank wall is a one-dimensional model (1D). For the correction factor of the linear equation, its first-order coefficient and constant term have a linear relationship with the initial pressure of the storage tank, and their R^2 values obtained from the fitting are greater than 0.99. Finally, we derived a new equation to calculate the final hydrogen temperature which can be combined with the 100% SOC inside the vehicle tank to determine the pressure target. The simulation results show that the final SOC obtained are all greater than 96% using the modified pressure target and the correction factor of the linear equation.

1.0 INTRODUCTION

Most current FCEVs use 35 or 70 MPa tanks to store hydrogen. Under such pressures, the filling process is subjected to restrictions for safety purposes: the maximum temperature in the vehicle tank should not exceed 85°C, the maximum pressure should not exceed 125% of the nominal working pressure (NWP), and the maximum state of charge (SOC) should not exceed 100% [1]. It is usually necessary to control the refuelling speed and pressure target to meet the above constraints. The pressure target control prevents overfilling, and the refuelling speed control prevents overheating [1]. Because the refuelling speed directly affects the enthalpy entering the storage tank per unit of time and the heat lost through the tank wall, which will eventually affect the temperature rise rate of the hydrogen in the storage tank.

In 2014, the Society of Automotive Engineers (SAE) released the fueling protocols for light duty gaseous hydrogen surface vehicles, SAE J2601, which includes a standard refuelling protocol called the lookup table method. For an actual refuelling event, which table to choose is determined according to the NWP of the vehicle tank (35 or 70 MPa), the capacity of the vehicle tank and the precooling category of the hydrogen refuelling station (HRS) (T40, T30 or T20). Then the pressure ramp rate (PRR) and pressure target in each table are determined according to the ambient temperature and the vehicle tank's initial pressure, respectively [1]. The lookup table method basically meets the refuelling requirements of FCVEs, but its refuelling performance can be further improved. Because the upper-limit temperature within the precooling category was used when formulating the PRR in the lookup table. The precooling temperature may not always be at the upper limit for an actual refuelling event so the PRR can be further improved.

To improve the lookup table method, Honda Corporation developed the MC method. Unlike tank material's mass and specific heat capacity, "MC" is not a direct physical constant. Instead, it combines many factors, including heat transferred to the tank valve and piping and to initial hydrogen inside the tank [13]. The MC method is an adaptive refuelling protocol that can dynamically adjust the PRR based on the dispenser's measurement of the mass flow rate, the ambient temperature, the initial pressure in the vehicle tank, and the delivered gas temperature and pressure during refuelling. Due to this feature, no precooling temperature category of T40 ($-40 \sim -33$°C), T30 ($-33 \sim -26$°C) and T20 ($-26 \sim -17.5$°C) for HRS is needed except for the limitation of $-40 \sim -15$°C. The MC method determines some unknown information in the lookup table method, such as the precooling temperature and mass flow rate of hydrogen distributed to the vehicle tank. Both can be obtained by measuring the delivered hydrogen during the refueling process by sensors installed on the dispenser of the HRS [2]. In the non-communication MC method, the pressure target is based on the final hydrogen temperature calculated by a simple analytical solution. Many assumptions are set in the calculation process. Such as, due to sun exposure or emptying, the initial temperature in the vehicle tank may not equal the ambient temperature. So, a hot or cold soak assumption is needed to protect against the worst case, resulting in a certain safety margin regarding temperature and pressure.

SAE J2601 also includes communication refuelling protocols based on the information transmitted from the vehicle tank to the dispenser. For communication refuelling, the PRRs of the lookup table and MC methods are the same as they are for non-communication refuelling, respectively. However, the determination of pressure targets is different from non-communication refuelling. The HRS will use the final hydrogen temperature of the vehicle tank obtained by communication to calculate the SOC. The refuelling will stop when the pressure of the dispenser outlet reaches the pressure corresponding to the 100% SOC in the vehicle tank. Simultaneously, the initial temperature during communication refuelling can be directly measured by the HRS, which is a definite temperature [2].

According to a review of the literature, there is not much research on the hydrogen refuelling protocol, especially the MC method, maybe due to the MC method being officially released in 2016. At the time of writing, only two studies were reported on the lookup table and the MC methods in SAE J2601. A study by Reddi et al. [3] in 2017 compared the SOC and filling time of the MC method with the lookup table method, using the H2SCOPE model. Another study by Chochlidakis et al. [4] in 2020 evaluated the refuelling time, SOC and total energy consumption of the two methods under different conditions. Some scholars have also tried to develop new protocols. For example, Chae et al. [5] developed a hydrogen communication refuelling protocol using a real-time response method, which optimizes refuelling time, precooling requirements, and energy consumption. Xiao et al. have developed dual-zone dual-temperature lumped parameter models for hydrogen filling [6].

In this work, to calculate the pressure target to control the refuelling stop, we introduced a dual-zone dual-temperature model that distinguishes the hydrogen temperature in the tank from the tank wall temperature to replace the dual-zone single-temperature model of the original MC method. We then expressed the total amount of heat transferred by convection between hydrogen and the inner wall of the storage tank during the whole refuelling process as an equation of final hydrogen temperature, final tank wall temperature, final refuelling time, tank inner surface area and the correction factor, thus deriving a new formula for calculating the final hydrogen temperature to determine when refuelling stops. The hydrogen filling process was simulated using the modified MC method, and all SOCs obtained were greater than 96%.

2.0 THERMODYNAMICS MODEL

2.1 Model Description and Assumption

With reference to SAE J2601 APPENDIX A [1], we developed a hydrogen filling model (0D1D), as depicted in Fig. 1. The hydrogen inside the tank is lumped parameter model (0D), and the tank wall is represented by a one-dimensional model (1D). The dual-zone dual-temperature model mentioned in the title, where the tank wall also is the lumped parameter model, will be only used in Section 4 to calculate the pressure target. The 0D1D model will be used to generate simulation data to fit the correction factor and verify the performance of the modified MC method.

Two assumptions are adopted in the model. (1) The thermal masses, such as pipes and valves involved in the system, are ignored. These thermal masses release heat into the cold hydrogen flow, increasing heat transferred to the vehicle tank. (2) All the pressure drops from the dispenser to the vehicle tank are lumped together for calculation.

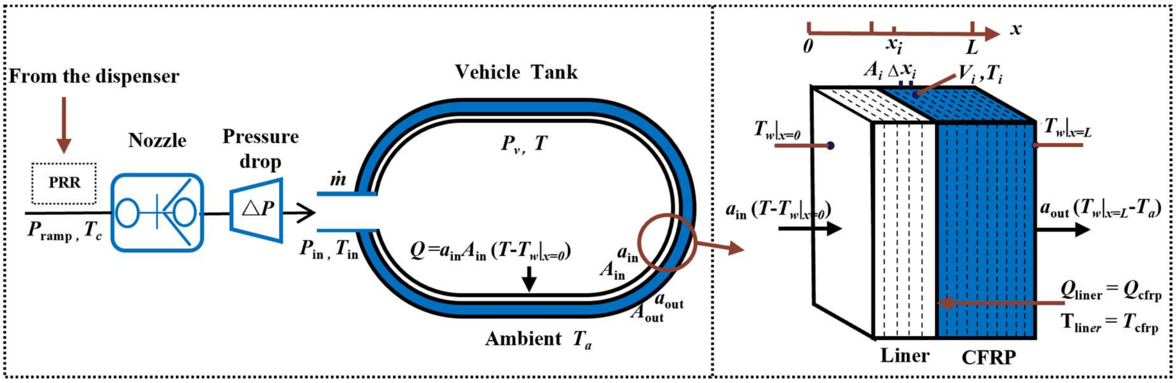

Figure 1. System structure diagram from the dispenser to the vehicle tank and partially enlarged diagram of the one-dimensional tank wall

2.2 Modeling Process

2.2.1 Hydrogen inside the Tank

The mass and energy conservation for hydrogen inside the hydrogen storage tank during filling and emptying can be expressed as [7]

$$\frac{dm}{dt} = \dot{m}_{\text{in}} - \dot{m}_{\text{out}} \tag{1}$$

$$\frac{d(mu)}{dt} = \dot{m}_{\text{in}}\, h_{\text{in}} - \dot{m}_{\text{out}}\, h_{\text{out}} + \dot{Q} \tag{2}$$

where $\dot{m}$, u and h are the mass flow rate, specific internal energy and specific enthalpy of hydrogen. The $u = c_v T$ and $h = c_p T$, where c_v and c_p are the specific heat capacity of hydrogen at constant volume and constant pressure. $\dot{Q}$ is the heat transfer rate between the tank wall and the hydrogen.

2.2.2 One-Dimensional Tank Wall

The heat conduction model of a flat plate can be used to analyze heat transfer inside the tank wall. Because the tank wall's thickness is thin compared to the inner diameter. At this point, the heat transfer equation along the tank wall's radial direction and boundary conditions can be written as [8]

$$\lambda_w \frac{\partial^2 T_w}{\partial x^2} = \rho_w c_w \frac{\partial T_w}{\partial t} \tag{3}$$

$$-\lambda_w \frac{\partial T_w}{\partial x}\bigg|_{x=0} = \alpha_{\text{in}}\,(T - T_w|_{x=0}) \tag{4}$$

$$-\lambda_w \frac{\partial T_w}{\partial x}\bigg|_{x=L} = \alpha_{\text{out}}\,(T_w|_{x=L} - T_a) \tag{5}$$

where T, T_w and T_a are the temperatures of the hydrogen, the tank wall and the ambient. λ_w, ρ_w and c_w are thermal conductivity, density and specific heat capacity of tank wall material. α_{in} and α_{out} are the heat transfer coefficients between the inner wall and hydrogen, and between the ambient and the outer wall, respectively. The tank wall can be studied using the resistance-capacitance method, equivalent to a finite volume analysis. So, Eq. (3) can be simplified to Eq. (6). $\dot{Q}_i$ is the heat transfer rate of component volume i, which is the sum of the heat transfer rates of two neighboring components.

$$\dot{Q}_i = -(\rho_w c_w \Delta V)_i \frac{dT_i}{dt} \quad (6)$$

$$\dot{Q}_i = \dot{Q}_{i-1} + \dot{Q}_{i+1} \quad (7)$$

$$\dot{Q}_{i-1} = \frac{T_i - T_{i-1}}{R_{i-1}} \quad (8)$$

where $R_i = \Delta x_i/(A_i \lambda_w)$. R_i, A_i and Δx_i are the tank wall cylindrical layer's thermal resistance, area and thickness.

For a compact horizontal tank, the heat transfer coefficient between the inner tank wall and the hydrogen can be expressed as [9]

$$a_{\text{in}} = \frac{0.14 \lambda \text{Re}_{d_{\text{in}}}^{0.67}}{D_{\text{in}}} \quad (9)$$

where Re is the Reynolds number, $\text{Re}_{d_{\text{in}}} = 4\dot{m}/\pi\mu d_{\text{in}}$. D_{in} and d_{in} are the internal diameters of the vehicle tank and the injector. λ, ρ and μ are the thermal conductivity, density and dynamic viscosity of the hydrogen obtained from the National Institute of Standards and Technology database [10].

2.2.3 Pressure Drops

A pressure drop occurs as hydrogen flows through pipes and valves.

$$\Delta P = k_p \frac{\dot{m}^2}{\rho} \quad (10)$$

where ΔP is the pressure drop. $\Delta P = P_{\text{ramp}} - P_v$, $P_{\text{ramp}} = P_{\text{initial}} + \text{PRR} \times t$. P_{ramp}, P_v and P_{initial} are the dispenser outlet pressure, the real-time and initial pressures inside the vehicle tank. k_p is the pressure drop coefficient.

3.0 REFUELLING PROCESS OF THE MC METHOD

The refuelling process of the MC method includes refuelling speed control and pressure target control.

3.1 Refuelling Speed

The dispenser adopts PRR to control the refuelling speed. A key parameter in the PRR calculation is called t_{final}, which is a function of the ambient temperature, initial pressure in the tank, tank volume and the mass average temperature (MAT). The MAT is calculated by the dispenser's measurement of the precooling temperature at the outlet. There are three stages to this process, as shown in Fig. 2.

(1) Rule 1: if $t(j) \leq 30$ s, $\text{MATC}_{(j)} = \text{MAT}_{\text{exp}}$
(2) Rule 2: if $t(j) > 30$ s and $P_{\text{control}(j)} \leq P_{\text{trans}}$, $\text{MATC}_{(j)} = \text{MAT30}_{(j)}$
(3) Rule 3: if $P_{\text{control}(j)} > P_{\text{trans}}$,

$$\text{MATC}_{(j)} = \text{MAT30}_{(j)} \left(\frac{P_{\text{final}} - P_{\text{control}(j)}}{P_{\text{final}} - P_{\text{trans}}}\right) + \text{MAT0}_{(j)} \left(1 - \frac{P_{\text{final}} - P_{\text{control}(j)}}{P_{\text{final}} - P_{\text{trans}}}\right) \quad (11)$$

The MAT, t_{final} and PRR can be calculated by

$$\text{MAT}_{(j)} = \frac{\sum_1^j (m_{(j)} - m_{(j-1)}) \times 0.5(T_{(j)} + T_{(j-1)})}{\sum_1^j (m_{(j)} - m_{(j-1)})} \quad (12)$$

$$t_{\text{final}(j)} = a \times \text{MATC}_{(j)}{}^3 + b \times \text{MATC}_{(j)}{}^2 + c \times \text{MATC}_{(j)} + d \quad (13)$$

$$\text{PRR}_{(j)} = \frac{P_{\text{final}} - P_{\text{ramp}(j)}}{t_{\text{final}(j)}\left(\frac{P_{\text{final}} - P_{\text{initial}}}{P_{\text{final}} - P_{\text{min}}}\right) - t_{(j)}} \quad (14)$$

where MAT_{exp}, MAT0, MAT30 and MATC are the MATs of expected at the end of the fill, calculated from the beginning of the fill, calculated from the 30th s, and that of the mathematical combination of MAT_{exp}, MAT0 and MAT30, respectively. P_{control} is the pressure that the dispenser control targets during filling. P_{trans} is a parameter in the MATC equation that controls how much MAT0 and MAT30 are weighted. P_{min} and P_{final} are the minimum and final pressures deriving the t_{final} equation coefficients.

Fig. 2 shows that at the end of the refuelling, MATC transitions to MAT0, and the MATC increases. Eq. (13) shows that the increase of MATC will lead to the increase of t_{final}. Then the PRR will gradually decrease, as seen in Eq. (14). The decrease in PRR will lead to a decrease in the pressure drop between the dispenser and the vehicle tank, increasing the final SOC inside the vehicle tank. This is an advantage of the MC method, similar to the "Top-off" refuelling in the lookup table method.

The set of coefficients (a, b, c, and d) in Eq. (13) are the function of ambient temperature, initial pressure in the tank and tank volume. The initial values of a, b, c and d are obtained for several specific ambient temperatures and tank volumes. Values for other ambient temperatures and tank volumes can be calculated using linear interpolation.

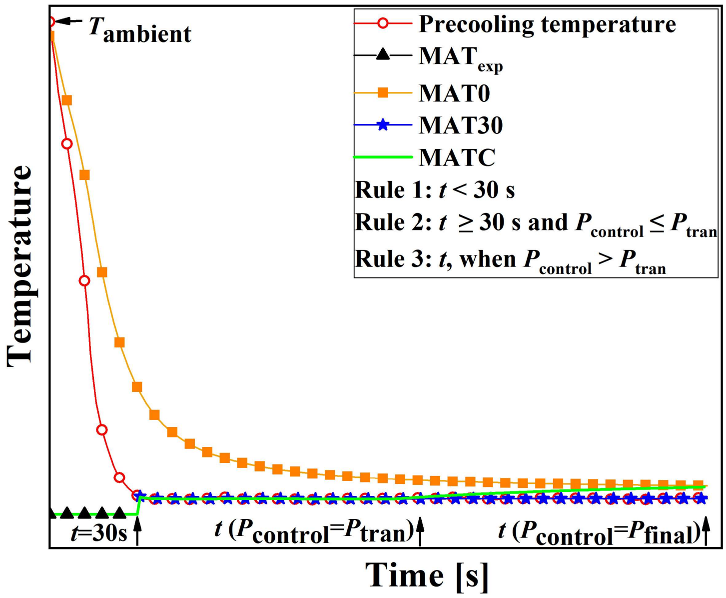

Figure 2. Three-stage rule for MATC to control refuelling speed in the MC method

3.2 Pressure Target

The MC method protocol is divided into communication and non-communication refuelling [1]. SAE obtained an analytical solution for the final hydrogen temperature in the vehicle tank for non-communication refueling, as Eq. (15). Then, the final hydrogen temperature will be used to calculate the pressure target by combining the 100% SOC inside the storage tank. The filling will stop when the dispenser outlet pressure reaches the pressure target. In Eq. (15), the "MC" can be calculated by Eq. (16). $T_{\text{adiabatic}}$ and $U_{\text{adiabatic}}$ can be calculated based on the mass average enthalpy of the entire refuelling process measured by the dispenser. The mass average enthalpy is a function of the mass flow rate, the gas temperature and pressure at the dispenser outlet.

$$T_{\text{final}} = \frac{m_2 c_v T_{\text{adiabatic}} + \text{MC}T_{\text{initial}}}{\text{MC} + m_2 c_v} \quad (15)$$

$$\text{MC} = \text{AC} + \text{BC}\ln\left(\frac{U_{\text{adiabatic}}}{U_{\text{initial}}}\right)^{1/2} + \text{GC}\left(1 - e^{-\text{KC}\Delta t}\right)^{\text{JC}} \quad (16)$$

where T_{initial} and U_{initial} are the initial hydrogen temperature and internal energy. $T_{\text{adiabatic}}$ and $U_{\text{adiabatic}}$ are the final hydrogen temperature and internal energy, assuming adiabatic. m_1 and m_2 are the initial and final hydrogen mass.

The SAE adopted the most conservative Cold Case Tank (70 MPa, 25 L, Type III) when determining the coefficients AC, BC, GC, KC and JC of Eq. (16) through simulation calculations [1]. The energy entering the tank when refuelling is proportional to the volume of the gas, and the heat lost is proportional to the inner surface area of the tank wall. So, the minimum temperature rise will occur in small-volume Type III tanks where the material is highly thermally conductive and has a low volume-to-surface area ratio. Cold Case Tank is a concept proposed in Table A3 of the SAE J2601 protocol, corresponding to the Hot Case Tank [1]. Using the most conservative Cold Case Tank to determine the coefficients of Eq. (16) can ensure safety for actual filling events. The parameters of the Cold Case Tank are shown in Table 1.

3.3 Validation of Refuelling Speed Control in MC Method and Validation of 0D1D Model

We programmed the MC method's control logic of the refuelling speed into our 0D1D model and implemented the refuelling process through the Simulink platform. The geometric parameters and thermodynamic properties of the storage tanks used in our study are shown in Table 1. Cold Case Tank is used for pressure target calculation in Section 4. As in Ref. [3], the initial pressure in the vehicle tank is 5 MPa, and the ambient and initial hydrogen temperatures are 25°C. Fig. 3 compares our model's results with Ref. [3]. We used the changing precooling temperature in Ref. [3] as input, and the model automatically calculated the PRR according to the MC method's three-stage rule of refuelling speed. Fig. 3 shows that PRR is in the first position in the first 30s, the second position from the 30s to P_{tran} and the third position from P_{tran} to the end, where PRR gradually decreases. The MC method realizes the dynamic control of the refuelling speed according to the precooling temperature, which is the main difference from the lookup table method.

Table 1. Geometric parameters and thermodynamic properties of tanks used in our study.

			Model Validation	Cold Case Tank
		Units	70 MPa Type IV [3]	1kg 70 MPa Type III [1]
Geometry	Internal gas volume	liter	129	25
	Total external length	mm	722	835
	Internal liner surface area	m^2	1.3	0.5
	External/Internal diameter	mm	600/513	240/200
	Liner/CFRP wall thickness	mm	5/38.3	3.25/16.7
	Liner/CFRP mass	kg	6.1/72.4	4.7/14.9
Properties	Liner/CFRP density	kg/m^3	975/1550	2700/1494
	Liner/CFRP thermal conductivity	W/m/K	0.3/0.3	164/0.74
	Liner/CFRP specific heat capacity	J/kg/K	1000/500	1106/1120

Our simulation results agree well with Ref. [3] regarding the PRR, mass flow rate, filling pressure at the dispenser outlet and hydrogen pressure in the vehicle tank. The hydrogen temperature in the storage tank for our 0D1D model increases rapidly in the early stage and tends to be stable in the later stage, while that of Ref. [3] has been slowly increasing. The final hydrogen temperature is about 5°C lower than Ref. [3]. The difference may be because, as mentioned in the model assumptions, we neglected thermal masses such as pipes and valves in the system, resulting in less heat flowing into vehicle tank.

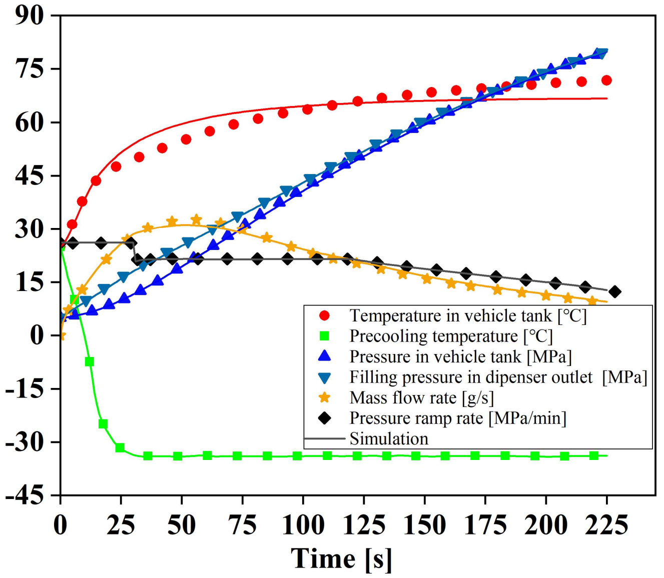

Figure 3. Comparison of simulation results of temperature, pressure, mass flow rate and PRR with Ref. [3] (Line: 0D1D model simulation; Dot: Ref. [3]).

4.0 PRESSURE TARGET FOR MODIFIED MC METHOD

The refuelling protocol in SAE J2601 must ensure that the hydrogen temperature in the tank does not exceed 85°C and the SOC does not exceed 100% under any refuelling conditions. Similar to SAE when determining the coefficients AC, BC, GC, KC and JC of Eq. (16), the most conservative Cold Case Tank was also adopted in the modified MC method.

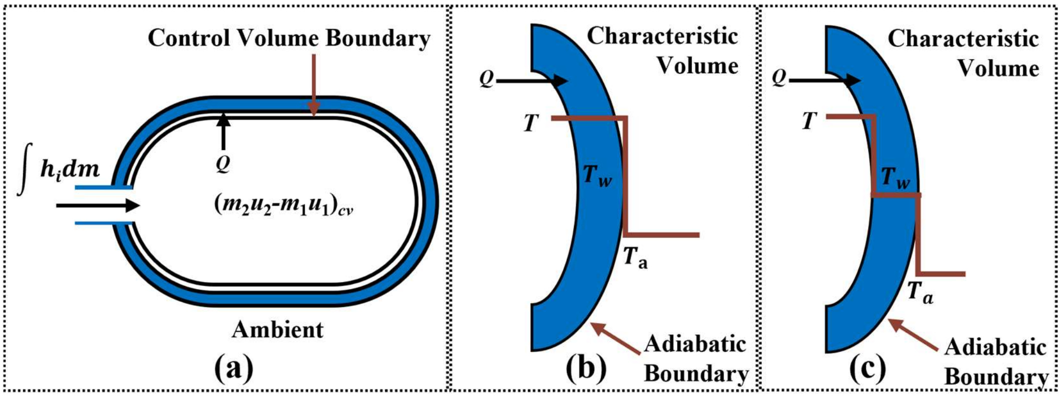

Figure 4. Control volume (a), characteristic volume in original (b) [11] and modified MC methods (c)

4.1 Pressure Target Determined by Dual-Zone Single-Temperature Model Used in Original MC Method

For hydrogen inside the control volume shown in Fig. 4(a), during a refuelling time of t_1-t_2, integrating Eq. (1) and (2) gives

$$m_2 - m_1 = \int_{t_1}^{t_2} \dot{m} dt \tag{17}$$

$$m_2u_2 - m_1u_1 = \int_{t_1}^{t_2} \dot{m}h_i dt - Q \quad (18)$$

As shown in Fig. 4(b), SAE assumed the characteristic volume of the tank wall to be a thermal mass with infinite thermal conductivity and convective heat transfer coefficient, and the tank wall temperature will equal the hydrogen temperature. So, we can define the model adopted by the original MC method as a dual-zone single-temperature model (hydrogen zone and tank wall zone). The SAE continued to assume that the outer boundary of the tank wall is adiabatic, and the heat transfer from the tank wall to the environment can be ignored. At this time, the energy conservation of tank wall can be expressed as

$$\mathrm{MC}(T_{\mathrm{final}} - T_{\mathrm{initial}}) = Q \quad (19)$$

Because of SAE's dual-zone single-temperature and adiabatic boundary assumptions, "MC" is no longer just the total heat capacity of the tank wall but includes the error caused by the assumptions. Eq. (16) shows that "MC" changes with the refuelling time. Generally speaking, the heat capacity of the tank wall material does not change significantly with refuelling time. From the Eq. (17)-(19), it follows that

$$\mathrm{MC} = \frac{m_1c_vT_{\mathrm{initial}} + \int_{t_1}^{t_2} \dot{m}h_i dt - m_2c_vT_{\mathrm{final}}}{T_{\mathrm{final}} - T_{\mathrm{initial}}} \quad (20)$$

Assume that the control volume inside the tank is adiabatic with the outside, So

$$U_{\mathrm{adiabatic}} = m_2c_vT_{\mathrm{adiabatic}} = m_1c_vT_{\mathrm{initial}} + \int_{t_1}^{t_2} \dot{m}h_i dt \quad (21)$$

Substituting Eq. (21) into (20) yields

$$\mathrm{MC} = \frac{m_2c_v(T_{\mathrm{adiabatic}} - T_{\mathrm{final}})}{T_{\mathrm{final}} - T_{\mathrm{initial}}} \quad (22)$$

Eq. (15) can be obtained from Eq. (22). Suppose the "MC" during refuelling can be determined individually. In that case, the final hydrogen temperature can be calculated using Eq. (15), combining the dispenser's measurement. These measurements include hydrogen's initial temperature and pressure inside the storage tank, delivered gas pressure and temperature, and mass flow rate. [12]. Then, the final hydrogen temperature will be used to calculate the pressure target by combining the 100% SOC inside the storage. Finally, the refuelling stops when the dispenser output pressure reaches the pressure target.

To determine the relationship between "MC" and initial/boundary conditions of refuelling, SAE carried out specific refuelling event simulations based on the hydrogen refuelling model similar to the 0D1D model in Section 2. Then they combined Eq. (22) to have obtained a large amount of "MC" simulation data. Finally, Eq. (16) was determined by observing the simulation data of "MC," evaluating the correlation of parameters, and using multiple linear regression.

4.2 Pressure Target Determined by Dual-Zone Dual-Temperature Model Used in Modified MC Method

As shown in Fig. 4(c), we introduced a dual-zone dual-temperature adiabatic model, which distinguishes the temperatures of hydrogen and tank wall, and regarded the wall as a lumped parameter model with uniform temperature. For the gas in the storage tank, it can be known from Newton's law of cooling that

$$\dot{Q} = A_{\mathrm{in}}a_{\mathrm{in}}(T - T_w) \quad (23)$$

Substituting Eq. (23) into Eqs. (18) and (19) yield

$$m_2c_v(T_{\mathrm{adiabatic}} - T_{\mathrm{final}}) = \int_{t_1}^{t_2} A_{\mathrm{in}}a_{\mathrm{in}}(T - T_w)dt \quad (24)$$

$$m_wc_w(T_{w\mathrm{fina}} - T_{\mathrm{initial}}) = \int_{t_1}^{t_2} A_{\mathrm{in}}a_{\mathrm{in}}(T - T_w)dt \quad (25)$$

where $T_{w\text{final}}$ is the final wall temperature. Assuming that the heat transfer coefficient a_{in} during the filling process is constant and defined as the average heat transfer coefficient a_{ave}, then

$$\int_{t_1}^{t_2} A_{\text{in}} a_{\text{in}} (T - T_w) dt = k_1 A_{\text{in}} a_{\text{ave}} \int_{t_1}^{t_2} (T - T_w) dt \tag{26}$$

where k_1 is the correction factor 1. According to the relationship between integral and area, Eq. (26) can be further transformed into

$$k_1 A_{\text{in}} a_{\text{ave}} \int_{t_1}^{t_2} (T - T_w) dt = k_1 k_2 a_{\text{ave}} A_{\text{in}} t_{\text{final}} (T_{\text{final}} - T_{w\text{final}}) \tag{27}$$

where k_2 is the correction factor 2. $k_1 k_2$ should be a function of factors such as the initial pressure and temperature inside the storage tank, the ambient temperature, etc.

Substituting Eq. (26) and (27) into Eq. (24) and (25) yields

$$m_2 c_v (T_{\text{adiabatic}} - T_{\text{final}}) = k_1 k_2 a_{\text{ave}} A_{\text{in}} t_{\text{final}} (T_{\text{final}} - T_{w\text{final}}) \tag{28}$$

$$m_w c_w (T_{w\text{final}} - T_{\text{initial}}) = k_1 k_2 a_{\text{ave}} A_{\text{in}} t_{\text{final}} (T_{\text{final}} - T_{w\text{fina}}\ ) \tag{29}$$

We define correction factor $K = k_1 k_2 a_{\text{ave}}$. So, the total amount of heat transferred by convection between hydrogen and the inner tank wall during the filling process can be expressed as an equation of final hydrogen temperature, final wall temperature, final refueling time, the tank inner surface area and the correction factor. We solve Eqs. (28) and (29), and obtain the final hydrogen and tank wall temperatures as

$$T_{\text{final}} = \frac{m_2 c_v T_{\text{adiabatic}} + m_w c_w T_{\text{initial}}}{m_2 c_v} - \frac{(m_w c_w)^2 T_{\text{initial}} (m_2 c_v + K A_{\text{in}} t_{\text{final}}) + K m_2 c_v T_{\text{adiabatic}} m_w c_w A_{\text{in}} t_{\text{final}}}{(m_2 c_v)^2 m_w c_w + K (m_2 c_v)^2 A_{\text{in}} t_{\text{final}} + K m_2 c_v m_w c_w A_{\text{in}} t_{\text{final}}} \tag{30}$$

$$T_{w\text{fina}}\ = \frac{K A_{\text{in}} T_{\text{final}} + m_w c_w T_{\text{initial}}}{m_w c_w + K A_{\text{in}} t_{\text{final}}} \tag{31}$$

where $m_w c_w$ is the total heat capacity of the Cold Case Tank wall and does not change with filling time, which can be calculated by using the mass average heat capacity, namely

$$m_w = m_{w\_\text{Liner}} + m_{w\_\text{CFRP}} \tag{32}$$

$$c_w = \frac{m_{w\_\text{Liner}}}{m_w} c_{w\_\text{Liner}} + \frac{m_{w\_\text{CFRP}}}{m_w} c_{w\_\text{CFRP}} \tag{33}$$

Finally, the pressure target will be calculated by combining the final hydrogen temperature and 100% SOC in the vehicle tank, the same as the original MC method.

4.3 Correction Factors Determined by Simulation Data from 0D1D Model

Similar to Eq. (15) in the original MC method, Eq. (30) shows that when we determine the value of K individually and then combine the parameters m_w, c_w, A_{in}, d_{in}, D_{in} of the Cold Case Tank, we can calculate the final hydrogen temperature to determine the pressure target to control the refuelling stop.

By Eq. (28) and $K = k_1 k_2 a_{\text{ave}}$, it can be obtained that

$$K = k_1 k_2 a_{\text{ave}} = \frac{m_2 c_v (T_{\text{adiabatic}} - T_{\text{final}})}{A_{\text{in}} t_{\text{final}} (T_{\text{final}} - T_{w\text{fina}}\ )} \tag{34}$$

By rewriting Eq. (9):

$$a_{\text{in}} = \frac{0.14 \left(\frac{4\dot{m}}{\pi \mu d_{\text{in}}}\right)^{0.67}}{D_{\text{in}}} = \frac{0.14 \left(\frac{4}{\pi \mu}\right)^{0.67} \left(\frac{\dot{m}}{d_{\text{in}}}\right)^{0.67}}{D_{\text{in}}} \tag{35}$$

We can have the average heat transfer coefficient:

$$a_{\text{ave}} = \bar{a}_{\text{in}} = \frac{0.14\lambda\left(\frac{4}{\pi\mu}\right)^{0.67}\left(\frac{\bar{m}}{d_{\text{in}}}\right)^{0.67}}{D_{\text{in}}} =: k_3\beta_{\text{ave}} \tag{36}$$

We define $k_3 = 0.14\lambda\left(\frac{4}{\pi\mu}\right)^{0.67}$ and $\beta_{\text{ave}} = \left(\frac{\bar{m}}{d_{\text{in}}}\right)^{0.67} / D_{\text{in}}$, where the average mass flow rate $\bar{m}$ can be obtained by the dispenser's measurement. Combining Eqs. (34) and (36), we get

$$k_1 k_2 k_3 \beta_{\text{ave}} = \frac{m_2 c_v (T_{\text{adiabatic}} - T_{\text{final}})}{A_{\text{in}} t_{\text{final}} (T_{\text{final}} - T_{w\text{final}})} \tag{37}$$

Setting correction factor $k = k_1 k_2 k_3$, we get

$$k = \frac{m_2 c_v (T_{\text{adiabatic}} - T_{\text{final}})}{A_{\text{in}} t_{\text{final}} (T_{\text{final}} - T_{w\text{fina}}) \left(\left(\frac{\bar{m}}{d_{\text{in}}}\right)^{0.67} / D_{\text{in}}\right)} = \frac{K}{\left(\left(\frac{\bar{m}}{d_{\text{in}}}\right)^{0.67} / D_{\text{in}}\right)} \tag{38}$$

That is, the correction factor *k* is obtained after introducing the average mass flow rate into the correction factor *K*. Referring to the modeling process of "MC" in the original MC method, we used the 0D1D model established in Section 2 for simulation. Then we substituted the obtained simulation data into Eq. (34) and (38), respectively, and finally obtained a lot of *K* and *k* simulation data. The initial and boundary conditions for simulation are shown in Table 2.

Table 2. Initial and boundary conditions for simulation to obtain *k* and *K* simulation data.

Tank	No.	Ambient Temp [°C]	Precooling Temp [°C]	Initial Pressure [MPa]	PRR [MPa/s] △=0.02	End of Fill Condition
1kg 70 MPa Type III Volume=25 L	1	0	−40	2	0.2-2.5	100% SOC
	2	20	−40	2	0.2-2.5	100% SOC
	3	40	−40	2	0.2-2.5	100% SOC
	4	0	−40	20	0.2-2.5	100% SOC
	5	20	−40	20	0.2-2.5	100% SOC
	6	40	−40	20	0.2-2.5	100% SOC
	7	0	−40	40	0.2-2.5	100% SOC
	8	20	−40	40	0.2-2.5	100% SOC
	9	40	−40	40	0.2-2.5	100% SOC
	10	0	−22.5	2	0.2-2.5	100% SOC
	11	20	−22.5	2	0.2-2.5	100% SOC
	12	40	−22.5	2	0.2-2.5	100% SOC
	13	0	−22.5	20	0.2-2.5	100% SOC
	14	20	−22.5	20	0.2-2.5	100% SOC
	15	40	−22.5	20	0.2-2.5	100% SOC
	16	0	−22.5	40	0.2-2.5	100% SOC
	17	20	−22.5	40	0.2-2.5	100% SOC
	18	40	−22.5	40	0.2-2.5	100% SOC

Fig. 5 shows the distribution of simulation data of *K* and *k* with final refuelling time, and the data points show apparent regularity. We found an interesting phenomenon: the ambient temperature and precooling temperature have less influence on the distribution of data points, but the initial pressure has a significant influence. Therefore, we ignore the ambient and precooling temperatures and only divide the whole data set according to different initial pressures. Finally, we fit *K* and *k* as polynomial equations related to the final refuelling time, as shown in Table 3. The coefficients of *K* basically show a linear relationship with the initial pressure, and the constant term basically remains unchanged. Therefore, we can use the calculation method of linear interpolation for a specific initial pressure. The *k* exhibits a linear relationship with the final refuelling time at each initial pressure, that is

$$k = Dt_{\text{final}} + E \quad (39)$$

where D and E also show a strong linear relationship with initial pressures. Through the fitting, $D = -0.0012P_{\text{initial}} + 0.1013$ (R^2=0.997), $E = 0.2982P_{\text{initial}} + 31.48$ (R^2=0.990).

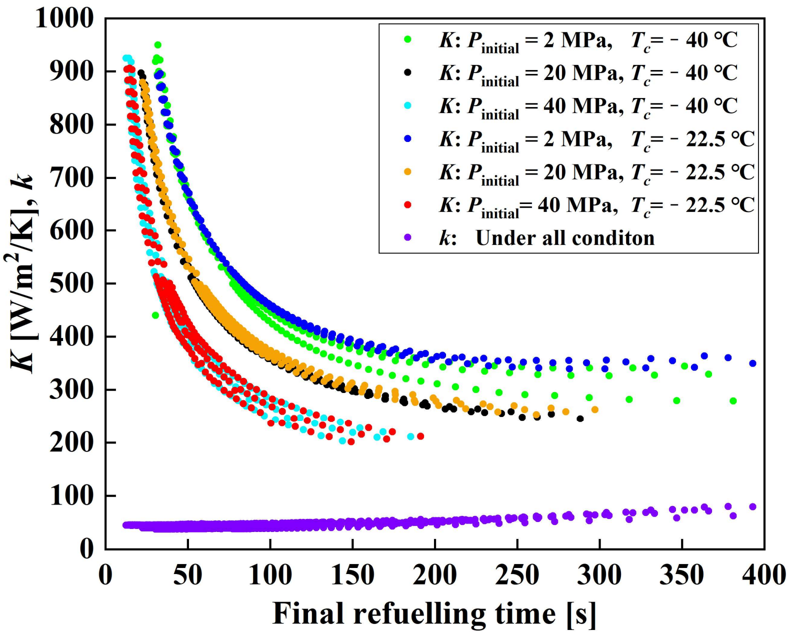

Figure 5. Distribution of K and k versus final refuelling time under different ambient temperatures, precooling temperatures (T_c) and initial pressures

Table 3. Fitting relationship of K and k versus final refuelling time under different initial pressures.

Initial Pressure [MPa]	y	A (t^4)	B (t^3)	C (t^2)	D (t^1)	E(t^0)	R^2
2	K	3E−07	−0.0003	0.1084	−16.319	1272.6	0.96
20		1E−06	−0.0008	0.1929	−21.785	1247.5	0.99
40		7E−06	−0.003	0.4944	−35.743	1278.2	0.97
2	k	0	0	0	0.098	32.429	0.90
20		0	0	0	0.078	36.774	0.95
40		0	0	0	0.051	43.725	0.91

4.4 Validation for SOC Results from Modified MC Method by the Data from 0D1D Model

We used the original MC method's refuelling speed control and modified pressure target control to simulate the actual refueling event. The modified MC method and original MC method are both based on the analytical solutions. Some assumptions, such as the adiabatic boundary and the tank wall's uniform temperature, are adopted in deriving the analytical solutions, leading to errors. The 0D1D model has been validated in section 3.3 and is more accurate considering the complex one-dimensional tank wall and complex heat transfer inside and outside the tank, so the results of the 0D1D model can be considered true and accurate and can be regarded as the reference. Table 4 shows that when the refuelling stops with 100% SOC using the modified MC method, the 0D1D model achieves a SOC greater than 96%. The coefficients of Eq. (39) are derived from the most conservative Cold Case Tank. If we want to improve the refuelling performance of the modified MC method further, we only need to update the coefficients of Eq. (39) using the parameters of the storage tank in the actual refuelling event. Likewise, if we want to improve the original MC method's refuelling performance, we just need to update the coefficients in Eq. (16), which are also obtained by fitting the simulation data based on Cold Case Tank.

Table 4. Validation for SOC Results from Modified MC Method by the Data from 0D1D Model

Initial Pressure [MPa]	Ambient Temp [°C]	t_{final} formula coefficient [1]				SOC	
		a	*b*	*c*	*d*	Modified MC method	0D1D model
2	40	0.01362863	-8.260816	1651.2	−108438	1	0.9944
	20	0.00202084	−0.72322	17.42	9783	1	0.9875
	0	0.00411881	−2.69214	590.798	−43511	1	0.9790
	−20	−0.0035514	3.035924	−837.335	75323	1	0.9718
	−40	0.0035207	−2.346046	525.1	−39448	1	0.9636
20	40	0.0008569	0.6705	−436.37	54608	1	0.9954
	20	0.00135946	−0.366034	−44.804	13224.7	1	0.9904
	0	0.00408545	−2.78004	636.37	−48976	1	0.9847
	−20	0.00056196	−0.1596	−15.1666	5153	1	0.9800
40	40	0.0008569	0.6705	−436.37	54608	1	0.9973
	20	0.00135946	−0.366034	−44.804	13224.7	1	0.9948
	−20	0.00056196	−0.1596	−15.1666	5153	1	0.9914

Table 5 shows the comparison between the modified with the original MC methods. Comparing Eq. (15) of the original method with Eq. (30) of the modified method, the modified MC method does not need additional information required by the HRS and can also achieve a satisfactory refuelling effect. Fig. 6 is the technical roadmap of this paper.

Table 5. Comparison between the modified MC method with the original MC method.

		Original MC method	Modified MC method
Refuelling speed		Eqs. (11) - (14)	Eqs. (11) - (14)
Pressure target	Model	Dual-zone single-temperature	Dual-zone dual-temperature
	Control equations	Eqs. (15) and (16)	Eqs. (30) and (39)

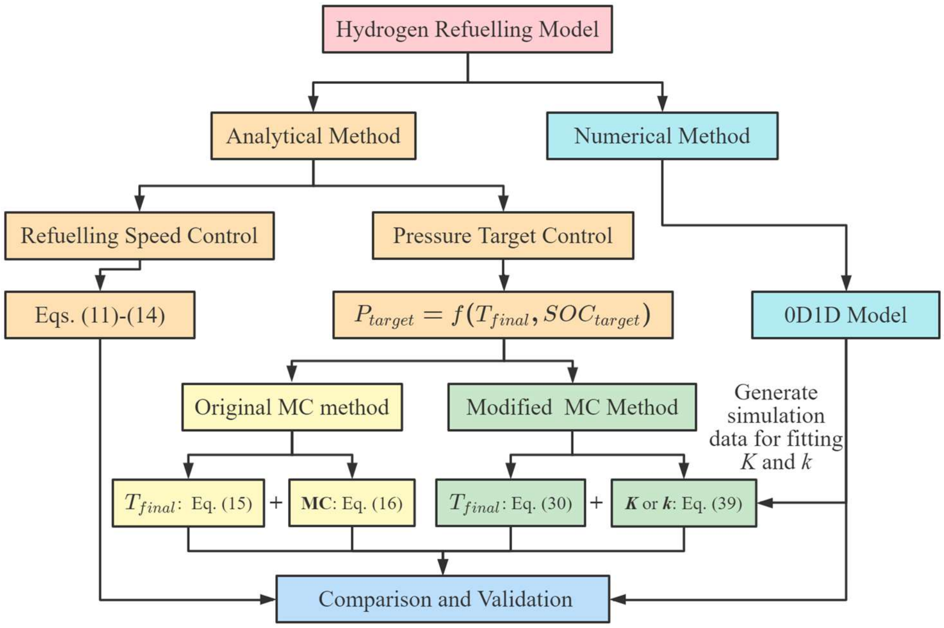

Figure 6. Technical roadmap in the paper

5 CONCLUSIONS

For the calculation method of the pressure target to control the refuelling stop, we introduced a dual-zone dual-temperature model that distinguishes the hydrogen temperature in the tank from the wall temperature to replace the dual-zone single-temperature model of the original MC method. We derived a new equation to calculate the final hydrogen temperature which can be combined with the 100% SOC inside the vehicle tank to determine the pressure target. The tank wall heat capacity in this new equation adopts the mass average heat capacity of the Cold Case Tank (70 MPa, 25 L, Type III), which does not change with the final refuelling time. Two kinds of correction factor equations were obtained by fitting many simulation data from the 0D1D model. The refuelling simulations were carried out using the linear correction factor equation. The specific conclusions are as follows:

(1) For a complete hydrogen filling process, the total amount of heat transferred by convection between hydrogen and the inner wall of the storage tank can be expressed as an equation of the final hydrogen temperature, final wall temperature, final refuelling time, tank inner surface area and correction factor.

(2) The correction factor can be expressed in two forms: one is a 4th-degree polynomial when the average mass flow rate is not introduced. The other is the linear equation after introducing the average mass flow rate. Similar to the original MC method, when fitting using the Cold Case Tank parameters, the correction factor of the linear equation can be obtained from $k = Dt_{\text{final}} + E$, where $D = -0.0012P_{\text{initial}} + 0.1013$ (R^2=0.997), $E = 0.2982P_{\text{initial}} + 31.48$ (R^2=0.990).

(3) The final SOC obtained are all greater than 96% using the modified pressure target and the correction factor of the linear equation.

ACKNOWLEDGMENT

This work was supported by the National Natural Science Foundation of China (52176191, 51476120), the China Merchants Vehicle Research Institute (Science and Technology Development Foundation: 20AKC3), and the Wuhan University of Technology Chongqing Research Institute (Research Project: YF 2021-08). Hao Luo also thanks the financial support from the China Scholarship Council (International Cooperation Training Project for Innovative Talents: 202106950012).

REFERENCES

1. Society of Automotive Engineers (SAE)., SAE J2601 (2020): Fueling protocols for light duty gaseous hydrogen surface vehicles, https://www.sae.org/standards/content/j2601_202005/.
2. Mathison, S., Harty, R., Cohen, J. and Gupta, N., Application of MC Method-Based H2 Fueling, SAE Technical Paper 2012-01-1223.
3. Reddi, K. and Elgowainy, A., Impact of hydrogen SAE J2601 fueling methods on fueling time of light-duty fuel cell electric vehicles, *Int J Hydrogen Energy*, **42**, No. 26, 2017, pp. 16675-16685.
4. Chochlidakis, C.G., Overall efficiency comparison between the fueling methods of SAEJ2601 using dynamic simulations, *Int J Hydrogen Energy*, **45**, No. 20, 2020, pp. 11842-11854.
5. Chae, C.K., Park, B.H., Huh, Y.S., Kang, S.K. and Kang, S.Y., Development of a new real time responding hydrogen fueling protocol, *Int J Hydrogen Energy*, **45**, No. 30, 2020, pp. 15390-15401.
6. Xiao, J.S., Wang, X., Zhou, X., Benard, P. and Chahine, R., A dual zone thermodynamic model for refueling hydrogen vehicles, *Int J Hydrogen Energy*, **44**, No. 17, 2019, pp. 8780-8790.
7. Xiao, J.S., Bénard, P. and Chahine, R., Charge-discharge cycle thermodynamics for compression hydrogen storage system, *Int J Hydrogen Energy*, **41**, No. 12, 2016, pp. 5531-5539.
8. Rothuizen, E., Mérida, W., Rokni, M. and Wistoft-Ibsen, M., Optimization of hydrogen vehicle refueling via dynamic simulation, *Int J Hydrogen Energy*, **38**, No. 11, 2013, pp. 4221-4231.
9. Bourgeois, T. and Ammouri, F., Evaluating the temperature inside a tank during a filling with highly pressurized gas, *Int J Hydrogen Energy*, **40**, No. 35, 2015, pp. 11748-11755.
10. National Institute of Standards and Technology (NIST). Reference fluid thermodynamic and transport properties database (REFPROP) Version 9.0 [software], https://www.nist.gov/srd/refprop.
11. Mathison, S., Handa, K., McGuire, T., Brown, T. and Goldstein, T., Field Validation of the MC Default Fill Hydrogen Fueling Protocol, *SAE Int. J. Alt. Power*, **4**, No. 1, 2015, pp. 130-144.
12. Schneider, J. and Meadows, G., Validation and Sensitivity Studies for SAE J2601, the Light Duty Vehicle Hydrogen Fueling Standard, *SAE Int. J. Alt. Power*, **3**, No. 2, 2014, pp. 257-309.
13. Harty, R., Mathison, S. and Gupta, N., Improving Hydrogen Tank Refueling Performance Through The Use Of an Advanced Fueling Algorithm - The MC Method, Proceedings of the National Hydrogen Association Conference, 4 May 2010, Long Beach.