HEAT TRANSFER MODELS FOR REFUELING SAFETY OF HYDROGEN VEHICLE

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ABSTRACT

Due to the simple structure and quick refueling process of the compressed hydrogen storage tank, it is widely used in fuel cell vehicles at present. However, temperature rise may lead to a safety problem during charging of a compressed hydrogen storage tank. To ensure the refueling safety, the thermal effects need to be studied carefully during hydrogen refueling process. In this paper, based on the mass and energy balance equations, a general heat transfer model for refueling process of compressed hydrogen storage tank is established. According to the geometric model of the tank wall structure, we have built three lumped parameter models: single-zone (hydrogen), dual-zone (hydrogen and tank wall) and triple-zone (hydrogen, tank wall liner and shell) model. These three lumped parameter models are compared with U.S. Naval gas charging model and SAE MC method based refueling model. Under adiabatic and diathermic conditions, four models are built in Matlab/Simulink software to simulate the hydrogen refueling process under corresponding conditions. These four models are: single-zone single-temperature (hydrogen), dual-zone single-temperature (hydrogen), dual-zone dual-temperature (hydrogen and tank wall temperatures), and triple-zone triple-temperature (hydrogen, tank wall liner and tank wall shell temperatures). By comparing the analytical solution and numerical solution, the temperature rise of the compressed hydrogen storage tank can be described. The analytical and numerical solutions on the heat transfer during hydrogen refueling process will provide theoretical guidance at actual refueling station, so as to improve the refueling efficiency and to enhance the refueling safety.

1.0 INTRODUCTION

Based on the SAE J2601, the maximum hydrogen temperature in the compressed hydrogen storage tank during hydrogen refueling cannot exceed 85°C [1]. Therefore, it is important to simulate the hydrogen refueling process of compressed hydrogen storage tank considering of the safety.

To ensure the safety during hydrogen refueling, many scholars have tried their best to study the thermal effects of hydrogen refueling process. Lyons, III J.T. [2] proposed U.S. Naval gas charging model and conducted a detailed analysis of the heat transfer process during charging of a high pressure gas storage tank and deduced the total differential equation. Woodfield, P.L. et al [3] conducted hydrogen refueling experiments using the tanks of different volumes and measured the temperature rise of hydrogen. Harty, R. et al [4] proposed the SAE MC method based refueling model and deduced the expression of hydrogen temperature in the hydrogen storage tank. Suryan A. et al [5] established a three-dimensional numerical model to simulate the hydrogen refueling process and obtained the hydrogen temperature distribution in the hydrogen storage tank by considering the effect of actual gas. Kim, S.C. et al [6] studied the thermodynamic properties of the Type IV hydrogen storage tank during hydrogen refueling process and quantified the change of hydrogen temperature. Ruffio E. et al [7] conducted a thermodynamic analysis of the hydrogen refueling process of the compressed hydrogen storage tank and the heat loss of the tank wall. De Miguel, N. et al [8, 9] studied the thermal effect of the type III and IV compressed hydrogen storage tanks during the charging and discharging process and studied the effect of the initial hydrogen temperature on hydrogen temperature. Bourgeois T. et al [10, 11] studied the hydrogen temperature during hydrogen refueling, and they also established a zero-dimensional model that can predict the hydrogen temperature in the hydrogen storage tank. Kuroki T. et al [12] proposed a dynamic simulation to study the method of hydrogen refueling and successfully predicted the temperature rise of hydrogen in Type III and Type IV compressed hydrogen storage tanks. Xiao, J.S. et al [13, 14, 15] established single-zone and dual-zone lumped parameter thermodynamic models for the gas charging/discharging process of the compressed hydrogen storage tank and derived the analytical solution of hydrogen temperature. Liu J. et al [16] conducted a CFD simulation of the hydrogen refueling process of Type III and IV hydrogen storage tanks with a volume of 150L and a normal working pressure of 35MPa.

Based on lumped parameter models we built, the U.S. Naval gas charging model, SAE MC method based refueling model and lumped parameter models are compared. Under adiabatic and diathermic conditions, different models are built in Matlab/Simulink software to simulate the hydrogen refueling process under corresponding conditions. By comparing the simulation results of analytical solution and numerical solution, it can be verified whether the temperature rise of hydrogen or tank wall can be accurately described.

2.0 MATHEMATICAL MODEL FOR HYDROGEN REFUELING PROCESS

During hydrogen refueling process, hydrogen mass and energy balance equation are:

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

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

During hydrogen refueling process, the tank wall energy balance equation is:

$$\frac{d(m_w c_w T_w)}{dt} = A_{\text{in}} a_{\text{in}} (T - T_w) - A_{\text{out}} a_{\text{out}} (T_w - T_f) \tag{3}$$

Since this paper studies the hydrogen charging process, the mass flow rate out of the tanks is set to 0, $\dot{m}_{\text{out}} = 0$, $\dot{m} = \dot{m}_{in}$ and $h = h_{in}$.

2.1 Analytical solution of single-zone lumped parameter model

A single-zone lumped parameter model is shown in Fig.1(a). During refueling hydrogen process, the effect of the tank wall in the system is ignored, that is, the heat is directly transferred from the gas to the external environment. So, the hydrogen mass and energy balance equation can be written as:

$$\frac{dm}{dt} = \dot{m} \tag{4}$$

$$\frac{d(mu)}{dt} = \dot{m} h + A_{\text{in}} a_{\text{in}} (T_f - T) \tag{5}$$

In our previous work[14], $\dot{m}$ is considered to be a constant, and according to the laws of thermodynamic, for an ideal gas with a constant specific heat, $u = c_v T$ and $h = c_p T_\infty$, then combining Eq. (4) and Eq. (5) and performing equation substitution, we obtain:

$$\frac{dT}{dt} = (1 + \alpha) \left(\frac{T^* - T}{t^* + t} \right) \tag{6}$$

By integrating Eq. (6), the analytical solution of hydrogen temperature of single-zone model is:

$$T = T^* - (T^* - T_0) \mu^{1+\alpha} \tag{7}$$

2.2 Analytical solution of dual-zone lumped parameter model

A dual-zone lumped parameter model is shown in Fig.1(b). Based on single-zone lumped parameter model, the tank wall is regarded as a whole, and the gas zone and the tank wall zone are considered. The heat is from the gas to the tank wall, and then from the tank wall to the external environment. In this model, the hydrogen mass balance equation is the same as Eq. (4), the tank wall energy balance equation is shown as Eq. (3), and the hydrogen energy balance equation can be written as:

$$\frac{d(mu)}{dt} = \dot{m}h + A_{\text{in}}a_{\text{in}}(T_w - T) \tag{8}$$

In our previous work [15], when integrating Eq. (8), the assumptions and symbols are basically the same as the single-zone model. The only difference is that T^* is defined as the characteristic time and $T^* = (\gamma T_\infty + \alpha T_w)/(1+\alpha)$, and the tank wall temperature T_w is assumed as a constant. So, the analytical solution of hydrogen temperature of dual-zone model in the form of "rule of mixture":

$$T = f_g T_0 + (1 - f_g)T^* \tag{9}$$

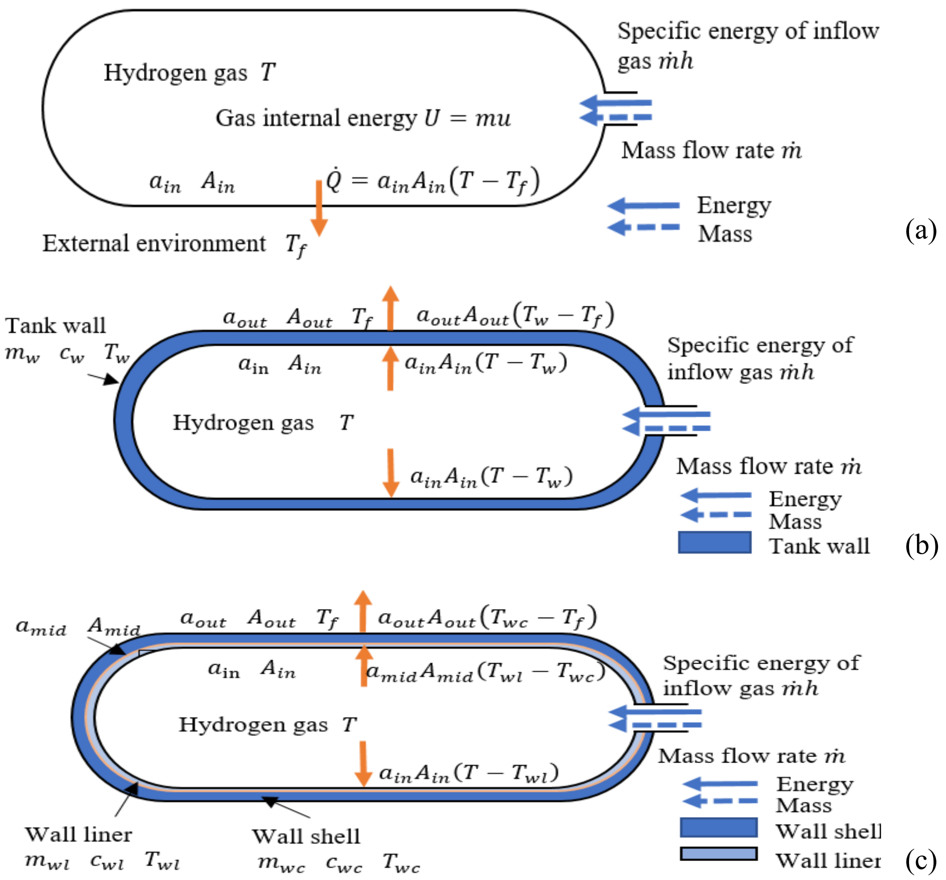


Figure 1. Model diagrams of single-zone model (a), dual-zone model (b) and triple-zone model (c)

Dividing both sides of the tank wall energy balance equation by $m_w c_w$, we obtain:

$$\frac{dT_w}{dt} = \frac{A_{in}a_{in}}{m_w c_w}(T - T_w) + \frac{A_{out}a_{out}}{m_w c_w}(T_f - T_w) \tag{10}$$

When T is assumed as a constant, by integrating Eq. (10) and performing equation substitution, Eq. (10) can be rewritten in the form of "rule of mixture" as:

$$T_w = f_w T_{w0} + (1 - f_w)(T\sigma_{in} + T_f\sigma_{out}) \tag{11}$$

Combining Eq. (9) and Eq. (11), the analytical solution of hydrogen temperature and tank wall temperature can be derived:

$$T = \frac{f_g T_0 + \frac{\gamma}{1+\alpha}(1 - f_g)T_\infty + \frac{\alpha}{1+\alpha}(1 - f_g)f_w T_{w0} + \frac{\alpha}{1+\alpha}(1 - f_g)(1 - f_w)\sigma_{out}T_f}{1 - \frac{\alpha}{1+\alpha}(1 - f_g)(1 - f_w)} \tag{12}$$

$$T_w = \frac{f_g T_{w0} + (1 - f_w)\sigma_{in} f_g T_0 + (1 - f_w)\sigma_{out}T_f + (1 - f_g)(1 - f_w)\frac{\gamma}{1+\alpha}\sigma_{in}T_\infty}{1 - \frac{\alpha}{1+\alpha}\sigma_{in}(1 - f_g)(1 - f_w)} \tag{13}$$

2.3 Triple-zone lumped parameter model

A triple-zone lumped parameter model is shown in Fig.1(c). On the basis of dual zone model, according to the different materials of the tank wall, the tank wall is divided into two parts: the liner and the shell. The heat is first transferred from the gas to the tank wall liner, then from the tank wall liner to the tank wall shell, and finally from the tank wall shell to the external environment.

The hydrogen mass and energy balance equation are the same as Eq. (4) and Eq. (8). The tank wall liner and shell energy balance equation are:

$$\frac{d(m_{wl}c_{wl}T_{wl})}{dt} = A_{\text{in}}a_{\text{in}}(T - T_{wl}) - A_{\text{mid}}a_{\text{mid}}(T_{wl} - T_{wc}) \tag{14}$$

$$\frac{d(m_{wc}c_{wc}T_{wc})}{dt} = A_{\text{mid}}a_{\text{mid}}(T_{wl} - T_{wc}) - A_{\text{out}}a_{\text{out}}(T_{wc} - T_f) \tag{15}$$

2.4 Comparison of three lumped parameter models

Single-zone, dual-zone and triple-zone lumped parameter models are built based on the geometric model of the tank wall structure. For single-zone model, the analytical solution of hydrogen temperature is the simplest, but the effect of the tank wall is ignored. For dual-zone model, comparing with single-zone model, it considers the effect of the tank wall and the analytical solution of hydrogen and tank wall temperature is more complicated but more practical, but the tank wall is assumed to be a whole. For triple-zone model, comparing with single-zone and dual-zone models, it is the most realistic, and not only considers the effect of the tank wall, but also divides the tank wall into inner liner and shell.

3.0 COMPARISON AND ANALYSIS OF MODEL

3.1 Single-zone single-temperature under adiabatic condition

As is shown in Fig.2(a), assuming that refueling process is adiabatic, that is, there are no heat transfer from hydrogen to environment. Therefore, the heat transfer coefficient between hydrogen and environment is approximately set to 0, then dimensionless heat transfer coefficient α≈0.

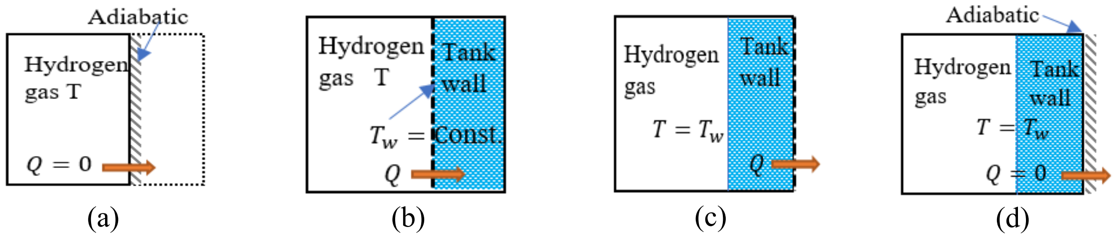


Figure 2. Diagrams of single-zone single-temperature model under adiabatic (a), diathermic(b) conditions, and dual-zone single-temperature model under diathermic (c) and adiabatic (d)conditions

So, under adiabatic condition, the analytical solution of hydrogen temperature of single-zone model, Eq. (7), can be rewritten as:

$$T = \gamma T_\infty - (\gamma T_\infty - T_0)\mu \tag{16}$$

In addition, using the symbols defined in this paper to rewrite Eq. (2) in Ref. [2] and comparing with Eq. (16), it is found that these two equations are consistent. So, under adiabatic condition, the single-zone model we built can be converted into the adiabatic charging model in Ref. [2].

3.2 Single-zone single-temperature under diathermic condition

As is shown in Fig.2(b), under diathermic condition, when tank wall heat capacity is larger than gas, it can be assumed that the tank wall temperature is constant, that is, the heat transferred from the gas is not enough to cause a significant effect on the tank wall temperature.

Under this condition, using the symbols defined in this paper to rewrite Eq. (4) in Ref. [2], when the tank wall temperature is constant, it is found that the equation is consistent with Eq. (9), which is the analytical solution of hydrogen temperature of dual-zone model. So, under diathermic condition, the dual-zone model we built can be converted into the diathermic charging model in Ref. [2] when the tank wall temperature is constant.

3.3 Dual-zone single-temperature under diathermic condition

As is shown in Fig.2(c), under diathermic condition, when the thermal conductivity of the tank wall internal wall is very strong, the thermal resistance of the tank internal wall can be ignored, that is, the tank wall temperature is equal to the gas temperature, and the heat transfer only exists between the tank wall outer surface and the external environment. Based on Eq. (8) and Eq. (10), $T_w = T$, the analytical solution of hydrogen temperature of dual-zone model can be written as:

$$T = (T_0 - T^*)\left(\frac{m_w c_w + c_v m_0}{m_w c_w + c_v m}\right)^{1+\alpha} + T^* \tag{17}$$

In addition, using the symbols defined in this paper to rewrite Eq. (6) in Ref. [2] and comparing with Eq. (17), it is found that these two equations are consistent. So, under diathermic condition, the dual-zone model we built can be converted into the charging model at constant mass flow with inside resistance negligible in Ref. [2].

3.4 Dual-zone single-temperature under adiabatic condition

As is shown in Fig.2(d), on the basis of section 3.3, it is further assumed that the external surface of tank wall is adiabatic, that is, the tank wall is regarded as a heat storage structure and absorbs all heat transferred from the hydrogen. Therefore, the heat transfer coefficient of the tank wall external surface $a_{out} = 0$, and dimensionless heat transfer coefficient $\alpha = A_{out}a_{out}/\dot{m}c_v = 0$. So, based on Eq. (17), the analytical solution of hydrogen temperature of dual-zone model under adiabatic condition can be written as:

$$T = (T_0 - \gamma T_\infty)\left(\frac{m_w c_w + c_v m_0}{m_w c_w + c_v m}\right) + \gamma T_\infty \tag{18}$$

Under this condition, based on Eq. (3) and (10) in Ref. [4], using the symbols defined in this paper, the solution of hydrogen temperature of SAE MC method based refueling model is derived:

$$T = \frac{m c_p T_\infty - m_0 c_p T_\infty + m_0 c_v T_0 + MCT_0}{MC + m c_v} \tag{19}$$

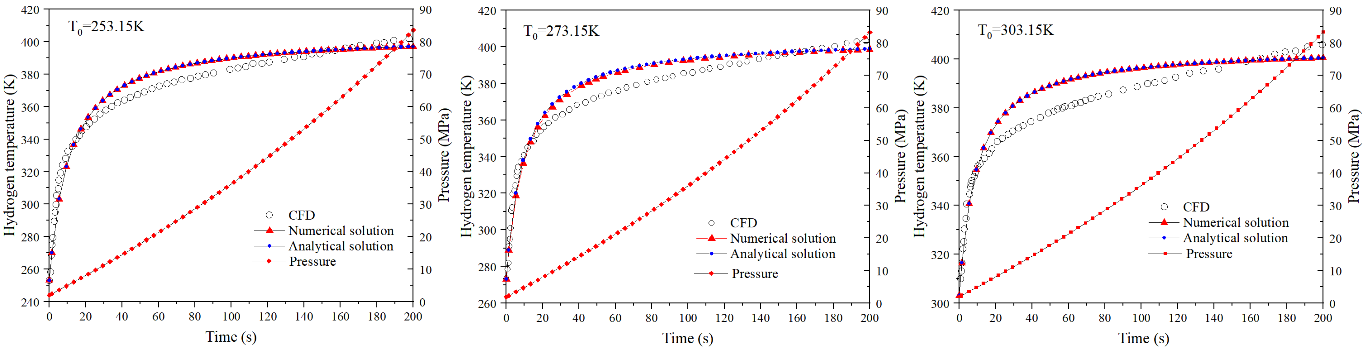
Where MC is a mathematical construction, combining mass M and specific heat capacity C , and its value varies with refueling time, refueling conditions, tank wall material, etc. When Comparing Eq. (19) with Eq. (18), it is found that if taking analogy of $m_w c_w$ to MC, that is MC $= m_w c_w$, Eq. (18) and Eq. (18) are consistent. So, under adiabatic condition, the dual-zone model we built can be converted into the SAE MC method based refueling model when MC $= m_w c_w$. However, it is worth noting that the units of MC and $m_w c_w$ are the same, both are kJ/K, but $m_w c_w$ in Eq. (18) is a constant and MC in Eq. (19) is a function varying with refueling time, refueling conditions, tank wall material, etc.

4.0 RESULTS AND DISCUSSION

4.1 Simulation of single-zone single-temperature model under adiabatic condition

For single-zone lumped parameter model, it is built based on the hydrogen mass and energy balance equations (Eq. (4) and Eq. (5)) in MATLAB/Simulink software. The analytical solution is obtained by writing codes in MATLAB Function module using M language based on Eq. (7). The numerical solution is obtained by integrating ordinary differential equations using integrator module in MATLAB/Simulink software. Under adiabatic condition, heat transfer coefficient of inner tank wall is set to 0, that is $a_{in} = 0$. The compressed hydrogen storage tank is type IV and its volume is 29L. Table 1 shows the value of physical parameters of the tank. The hydrogen refueling process, in which initial hydrogen temperature is 253.15K, 273.15K and 303.15K are simulated when initial hydrogen pressure is 2MPa and the relevant parameters are shown in Table 2. The simulation results are compared with the results of CFD [9] to verify the validity of this model.

As is shown in Fig.3, it is found that the analytical solution and numerical solution of hydrogen temperature are consistent, and hydrogen temperature simulated in MATLAB/Simulink software is close to the simulation results of CFD. Therefore, under adiabatic conditions, the single-zone single-temperature model is effective to simulate the hydrogen refueling process and the analytical solution of hydrogen temperature of this model can describe the temperature rise of hydrogen.



(a) (b) (c)

Figure 3. Comparison of hydrogen temperature under different initial hydrogen temperatures

Table 1. Physical parameters of the compressed hydrogen storage tank

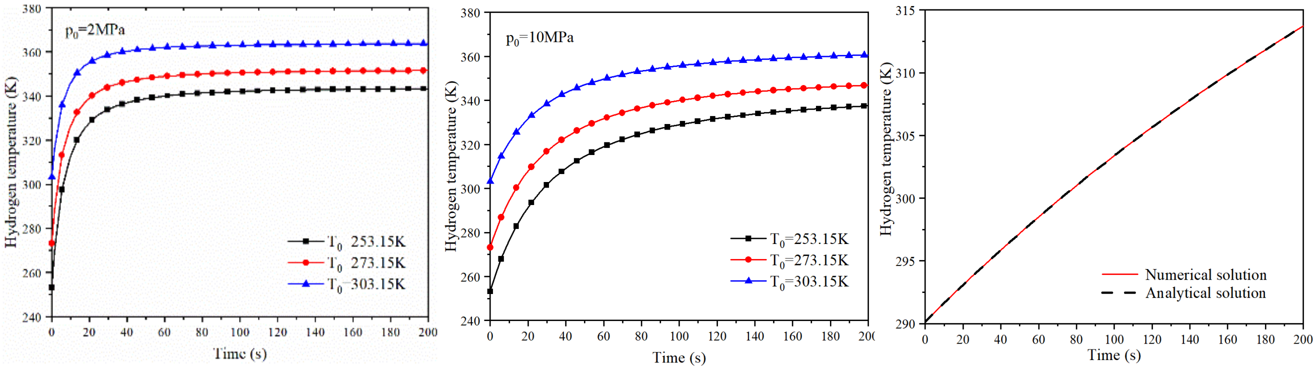
Parameter	Physical definition	Value
V	Volume of the tank, m^3	0.029
$D_{external}$	Outer diameter of the tank, m	0.279
$D_{internal}$	Inner diameter of the tank, m	0.230
L	Length of the tank, m	0.827
NWP	Normal working pressure of the tank, MPa	70
m_w	Mass of the tank wall, kg	32.9
c_{wliner}	Specific heat capacity of tank wall liner, kJ/kg/K	1.58
c_{wshell}	Specific heat capacity of tank wall shell, kJ/kg/K	1.12

Table 2. Experimental parameters of the compressed hydrogen storage tank

Parameter	Physical definition	Value
c_p	Specific heat capacity at constant pressure, kJ/kg/K	14.913
c_v	Specific heat capacity at constant volume, kJ/kg/K	10.060
T_0	Initial hydrogen temperature, K	253.15/273.15/303.15
T_∞	Inflow hydrogen temperature, K	273.15
T_f	Ambient temperature, K	273.15
m_0	Initial hydrogen mass in the tank, kg	0.258
$\dot{m}$	Mass flow rate, kg/s	0.005
p_0	Initial hydrogen pressure, MPa	2

4.2 Simulation of single-zone single-temperature model under diathermic condition

As for the single-zone single-temperature model under diathermic condition, heat exchange in the compressed hydrogen storage tank is considered. Therefore, the heat transfer coefficient of the inner wall of hydrogen storage tank is set to 0.06, that is $a_{in} = 0.06$. Under this condition, the relevant parameters are the same with the simulation under adiabatic condition. As is shown in Fig.9, the hydrogen refueling process under the conditions of initial hydrogen temperature of 253.15K, 273.15K and 303.15K when initial hydrogen pressure is 2MPa and 10MPa is simulated respectively. By comparing the simulation results under adiabatic and diathermic conditions, the effect of heat transfer in the hydrogen refueling process of the compressed hydrogen storage tank can be distinguished. As is shown in Fig.4(a) and (b), when initial hydrogen pressure is the same, it is found that the initial hydrogen temperature is different, the final hydrogen temperature has a significant difference. So, by comparing the final hydrogen temperature when initial hydrogen pressure is 2MPa under adiabatic and diathermic conditions, it is found that the initial hydrogen temperature has a more significant effect on the final hydrogen temperature under diathermic condition.



(a) (b) (c)

Figure 4. Comparison of hydrogen temperature under different initial hydrogen temperature at pressure 2MP (a) and 10MP (b), and comparison of numerical and analytical solutions of hydrogen temperature (c)

4.3 Simulation of dual-zone single-temperature model under diathermic conditions

As for the dual-zone single-temperature model under diathermic condition, the hydrogen and tank wall temperature are assumed to be equal. The model is built based on the hydrogen and the tank wall energy balance equations (Eq. (8) and Eq. (10)) in MATLAB/Simulink software. The analytical solution is obtained by writing codes in MATLAB Function module using M language based on (Eq. (17) The compressed hydrogen storage tank is type IV whose volume is 72L and the relevant parameters and conditions of hydrogen refueling are respectively shown in Table 3 and 4.

As is shown in Fig.4(c), it is found that these two curves have a good agreement. In addition, it can also be found intuitively that the trend of hydrogen temperature with time is approximately linear, which is because the heat capacity of the wall material is much greater than the heat capacity of the hydrogen in the tank, and it is assumed that the tank wall temperature and the hydrogen temperature are equal, that is, the thermal resistance of the inner wall of the tank is very small, and the degree of heat transfer between the hydrogen and the inner wall of the tank is relatively large. Therefore, under diathermic condition, the dual-zone single-temperature model is effective to simulate the hydrogen refueling process and the analytical solution of hydrogen temperature of the dual-zone single-temperature model can describe the temperature rise of hydrogen when the hydrogen and tank wall temperature are equal.

Table 3. Physical parameters of the compressed hydrogen storage tank

parameter	Physical definition	Value
V	Volume of the tank, m^3	0.072
D	Diameter of the tank, m	0.403
L	Length of the tank, m	0.9
NWP	Normal working pressure of the tank, MPa	35
δ	Thickness of the tank wall, m	0.025
m_w	Mass of the tank wall, kg	37
c_w	Specific heat capacity of tank wall, kJ/kg/K	0.9
A_{in}	Internal surface area of the tank, m^2	0.942
A_{out}	External surface area of the tank, m^2	1.139

Table 4. Experimental parameters of the compressed hydrogen storage tank

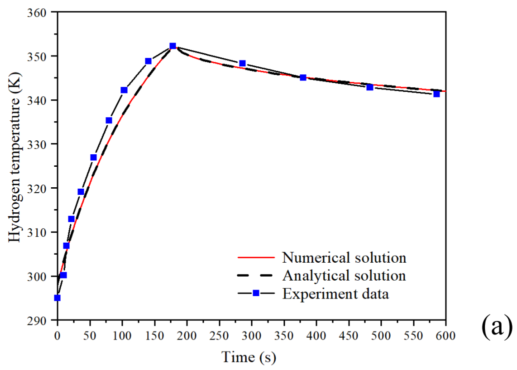
Parameter	Physical definition	Value
a_{in}	Heat transfer coefficient between hydrogen and tank wall, kW/m^2/K	0.06
a_{out}	Heat transfer coefficient between tank wall and environment kW/m^2/K	0.01
c_p	Specific heat capacity at constant pressure, kJ/kg/K	14.615
c_v	Specific heat capacity at constant volume, kJ/kg/K	10.315
m_0	Initial hydrogen mass in the tank, kg	0.564
$\dot{m}$	Mass flow rate, kg/s	0.005
T_0	Initial hydrogen temperature, K	290.15
T_∞	Inflow temperature, K	290.15
T_w	Initial tank wall temperature, K	293.15
T_f	Ambient temperature, K	293.15

4.4 Simulation of dual-zone single-temperature model under adiabatic conditions

As for the dual-zone single-temperature model under adiabatic condition, the outer wall of the compressed hydrogen storage tank is assumed to be adiabatic. The model is built in MATLAB/Simulink software based on Eq. (3) and (10) in Ref. [4]. The analytical solution is obtained by writing codes in MATLAB Function module using M language based on Eq. (18) The compressed hydrogen storage tank is type III and its volume is 171L and the relevant parameters of compressed hydrogen storage tank are shown in Table 5. The analytical and numerical solution of hydrogen temperature are compared with experimental data [4] to verify the effectiveness of the model.

Table 5. Experimental parameters of the compressed hydrogen storage tank

Parameter	Physical definition	Value
V	Volume of the tank, m^3	0.171
m_0	Initial hydrogen mass in the tank, kg	0.275
$\dot{m}$	Mass flow rate, kg/s	0.0024
c_p	Specific heat capacity at constant pressure, kJ/kg/K	14.913
c_v	Specific heat capacity at constant volume, kJ/kg/K	10.316
T_0	Initial hydrogen temperature, K	298.15
T_∞	Inflow temperature, K	298.15
T_f	Ambient temperature, K	298.15
p_0	Initial hydrogen pressure, MPa	2
NWP	Normal working pressure of the tank, MPa	35



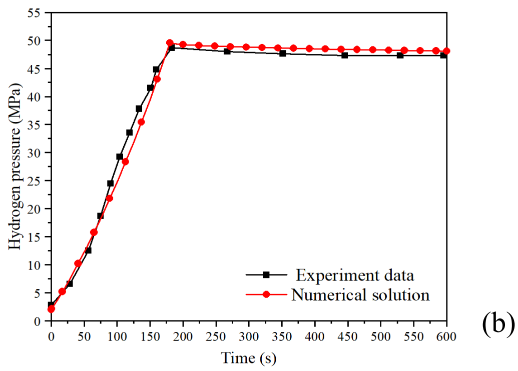


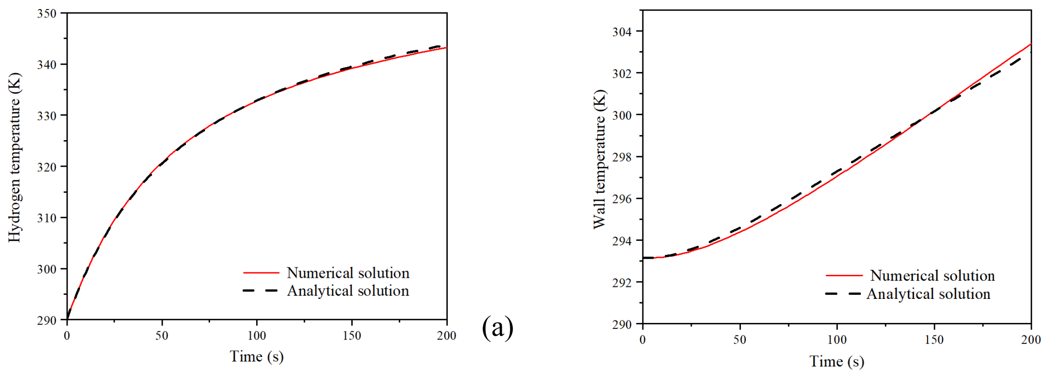
Figure 5. Comparison of simulated and experimental results of hydrogen temperature (a) and pressure (b)

As is shown in Fig.5, it is found that the simulated results are close to the experimental data. Therefore, under adiabatic condition, the dual-zone single-temperature model is effective to simulate the hydrogen refueling process. In addition, by comparing the analytical and numerical solutions, it can be found that the analytical solution of hydrogen temperature of dual-zone single-temperature model under adiabatic conditions can describe the temperature rise of hydrogen under the premise that the value of MC corresponds to the type of hydrogen storage tank and the hydrogen refueling conditions.

4.5 Simulation of dual-zone dual-temperature model under diathermic condition

For the dual-zone lumped parameter model, the temperature rises of hydrogen and the tank wall can be described at the same time, so it is called the dual-zone dual-temperature lumped parameter model. As for the simulation of dual-zone dual-temperature model under adiabatic condition, it has been confirmed that analytical solution of hydrogen and tank wall temperature can accurately describe the temperature rises of hydrogen and tank [15].

Under diathermic condition, the model is built based on the hydrogen mass and energy balance equations and the tank wall energy balance equations (Eq. (3), Eq. (4) and Eq. (8)) in MATLAB/Simulink software. The analytical solution is obtained by writing codes in MATLAB Function module using M language based on Eq. (12) and Eq. (13). The compressed hydrogen storage tank is type IV, its volume is 72L, and the relevant parameters is the same with Table 3 and 4. As is shown in Fig.6, it can be seen that the numerical and analytical solutions of the hydrogen temperature are highly consistent. As for the tank wall temperature, the general trend of the temperature rises of the two curves is the same. Therefore, under diathermic condition, analytical solution of hydrogen and tank wall temperature in this model can accurately describe the temperature rises of hydrogen and tank wall.



(a) (b)

Figure 6. Comparison of numerical and analytical solutions of hydrogen (a) and wall (b) temperature

4.6 Simulation of triple-zone triple-temperature model

Based on the triple-zone lumped parameter model, the hydrogen, tank wall liner and shell temperature can be described simultaneously, so it is called a triple-zone triple-temperature lumped parameter model. The model is built in MATLAB/Simulink software based on Eq. (4), Eq. (8), Eq. (14) and Eq. (15). The volume of Type III and IV compressed hydrogen storage tank both are 150L, normal working pressure are 35MPa, the time of refueling hydrogen is 3 minutes and the time of standing is 10 minutes. The relevant parameters of compressed hydrogen storage tank are shown in Table 6, 7 and 8. The results of simulation are compared with data from CFD [16] and are shown in Fig.11.As for Fig.7(a), the trend of temperature rises and the maximum hydrogen temperature at the end of refueling hydrogen are respectively consistent. As for Fig.7(b), as for type IV compressed hydrogen storage tank, the two curves are consistent during the process of refueling hydrogen. As for type III compressed hydrogen storage tank, the change trend of the two curves are consistent and the maximum difference in the temperature of tank wall liner is 3K. As is shown in Fig.7(c), as for type IV compressed hydrogen storage tank, the maximum difference in the temperature of tank wall shell is about 3K. As for type III compressed hydrogen storage tank, the two curves have a good agreement.

So, the triple-zone triple-temperature lumped parameter model can simulate the hydrogen refueling process of different types of compressed hydrogen storage tanks and describe the temperature rise of hydrogen, tank wall liner and shell for the type III compressed hydrogen storage tank.

Table 6. Physical parameters of materials of the compressed hydrogen storage tank wall

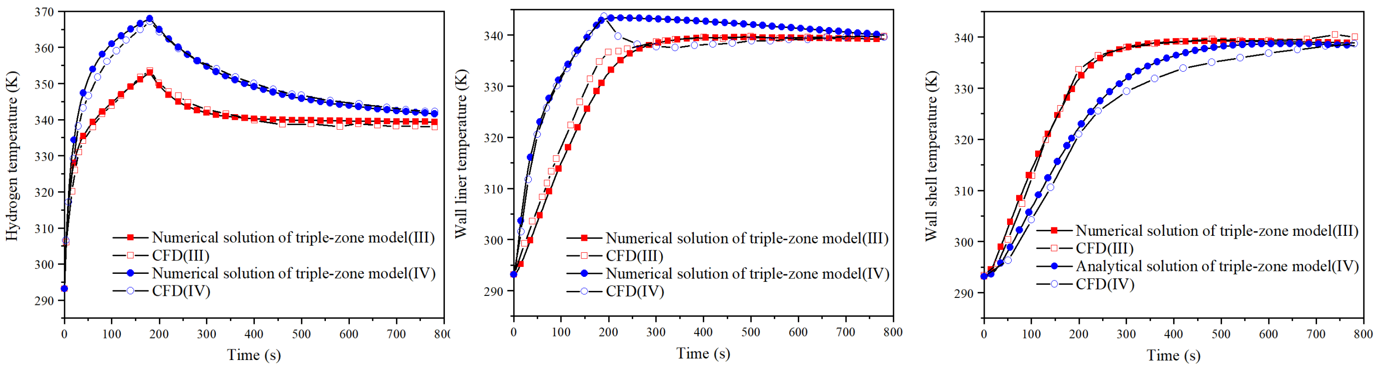
type	Density, kg/m^3	Specific heat capacity, kJ/kg/K
Liner of Type III tank	2700	0.902
Liner of Type IV tank	952	2.09
Shell of Type III and IV tank	1513	0.92

Table 7. Physical parameters of the compressed hydrogen storage tank

Parameter	Physical definition	Value
V	Volume of the tank, m^3	0.15
D_{in}	Inner diameter of the tank, m	0.376
D_{out}	Outer diameter of the tank, m	0.4
L	Length of the tank, m	1.652
NWP	Normal working pressure of the tank, MPa	35
δ_{in}	Thickness of the tank wall liner, m	0.004
δ_{out}	Thickness of the tank wall shell, m	0.009

Table 8. Experimental parameters of the compressed hydrogen storage tank

Parameter	Physical definition	Value
$\dot{m}$	Mass flow rate, kg/s	0.0136
m_0	Initial hydrogen mass, kg	0.365
a_{in}	Heat transfer coefficient of hydrogen and tank wall liner, kW/m^2/K	0.14(III)/0.1(IV)
a_{mid}	Heat transfer coefficient of tank wall liner and shell, kW/m^2/K	0.14(III)/0.1(IV)
a_{out}	Heat transfer coefficient of tank wall shell and environment, kW/m^2/K	0.001(III)/0.005(IV)
c_p	Specific heat capacity at constant pressure, kJ/kg/K	14.615
c_v	Specific heat capacity at constant volume, kJ/kg/K	10.315
T_0	Initial hydrogen temperature, K	293.15
T_∞	Inflow temperature, K	293.15
T_w	Initial tank wall temperature, K	293.15
T_f	Ambient temperature, K	293.15



(a) (b) (c)

Figure 7. Comparison of hydrogen (a), tank wall liner (b) and tank wall shell (c) temperature between numerical solution of three-zone model and CFD simulation result

5.0 CONCLUSIONS

In this study, by comparing the U.S. Naval gas charging model, SAE MC method based refueling model with lumped parameter models we built, the heat transfer conditions of four models: single-zone single-temperature adiabatic condition, single-zone single-temperature diathermic condition, dual-zone single-temperature diathermic condition, dual-zone single-temperature adiabatic condition are summarized, and different models are built in MATLAB/Simulink software, so that the analytical and numerical solutions of hydrogen or tank wall temperature can be compared. As for the single-zone single-temperature model, the dual-zone single-temperature model and the dual-zone dual-temperature model, the analytical solutions of hydrogen or tank wall temperature can describe the temperature rise during hydrogen refueling process under corresponding conditions to ensure the refueling safety. As for the triple-zone triple-temperature model, it can simulate the hydrogen refueling process of different types of compressed hydrogen storage tanks and describe the temperature rise of hydrogen, tank wall liner and shell for the type III compressed hydrogen storage tank. Therefore, this study will provide certain theoretical guidance at actual refueling station and help to set up a formula based approach of refueling protocol for gaseous hydrogen vehicles in the future.

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NOMENCLATURE

a_{in}	heat transfer coefficient at inner surface, kW/m²/K	$\dot{Q}$	heat exchange between tank wall and hydrogen per unit time, kW/s, $\dot{Q} = A_{in}a_{in}(T - T_f)$
a_{mid}	heat transfer coefficient between liner and shell, kW/m²/K	R_i	heat resistance between hydrogen and tank wall, K/W
a_{out}	heat transfer coefficient at outer surface, kW/m²/K	R_∞	heat resistance between external environment and tank wall, K/W
A_{in}	internal surface area of tank, m²	t	time variable, s
A_{mid}	contact area between liner and shell, m²	t^*	characteristic time, $t^* = m_0/\dot{m}$, s
A_{out}	external surface area of tank, m²	T	temperature, K
c_p	specific heat capacity at constant pressure, kJ/kg/K	T_0	initial hydrogen temperature in tank, K
c_v	specific heat capacity at constant volume, kJ/kg/K	T_f	ambient temperature, K
c_w	specific heat of tank wall, kJ/kg/K	T_w	temperature of tank wall, K
c_{wl}	specific heat of tank wall liner, kJ/kg/K	T_{w0}	initial temperature of tank wall, K
f_g	weight of rule of mixture, $f_g = \mu^{1+\alpha}$	T_{wl}	temperature of tank wall liner, K
f_w	weight of rule of mixture, $f_w = e^{-(\alpha_{win}+\alpha_{wout})t}$	T_{wc}	temperature of tank wall shell, K
c_{wc}	specific heat of tank wall shell, kJ/kg/K	T_∞	inflow hydrogen temperature, K
h	specific enthalpy of hydrogen, kJ/kg	T^*	characteristic temperature, $T^* = (\gamma T_\infty + \alpha T_w)/(1+\alpha)$, K
h_{in}	specific enthalpy of inflow hydrogen, kJ/kg	u	specific internal energy, kJ/kg
h_{out}	specific enthalpy of outflow hydrogen, kJ/kg	***Greek symbols***	
m	hydrogen mass in tank, kg	α	dimensionless heat transfer coefficient, $\alpha = a_{in}A_{in}/(c_v\dot{m})$
$\dot{m}$	hydrogen mass flow rate, kg/s	α_{win}	$\alpha_{win} = A_{in}a_{in}/m_w c_w$
m_0	initial hydrogen mass in tank, kg	α_{wout}	$\alpha_{wout} = A_{out}a_{out}/m_w c_w$
$\dot{m}_{in}$	hydrogen mass inflow rate, kg/s	γ	ratio of specific heats, $\gamma = c_p/c_v$
$\dot{m}_{out}$	hydrogen mass outflow rate, kg/s	μ	fraction of initial mass, $\mu = m_0/m$
m_w	mass of tank wall, kg	σ_{in}	$\sigma_{in} = \alpha_{win}/(\alpha_{win} + \alpha_{wout})$
m_{wl}	mass of tank wall liner, kg	α_{wout}	$\alpha_{wout} = A_{out}a_{out}/m_w c_w$
m_{wc}	mass of tank wall shell, kg		

REFERENCES

1. SAE. J2601, Fueling Protocols for Light Duty Gaseous Hydrogen Surface Vehicles, SAE Fuel Cell Standard Committee, 2016.
2. Lyons, III J.T., Heat Transfer Considerations in a Pressure Vessel Being Charged, 1969, U.S. Naval Postgraduate School, California.
3. Woodfield, P.L., Takano, T. and Monde, M., Characteristics of Heat Transfer for Hydrogen and Wall during Filling Hydrogen into Actual Tank at High Pressure, Thermal Engineering Heat Transfer Summer Conference, American Society of Mechanical Engineers Digital Collection, 2007, pp. 1069-1076.
4. 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, 2010, pp. 1026.
5. Suryan A., Kim H.D. and Setoguchi T., Three Dimensional Numerical Computations on the Fast Filling of a Hydrogen Tank under Different Conditions, *International Journal of Hydrogen Energy*, **37**, No. 9,2012, pp. 7600-7611.
6. Kim, S.C., Lee, S.H. and Yoon, K.B., Thermal Characteristics during Hydrogen Fueling Process of Type IV Cylinder, *International Journal of Hydrogen Energy*, **35**, No. 13, 2010, pp. 6830-6835.
7. Ruffio E., Saury D. and Petit D., Thermodynamic Analysis of Hydrogen Tank Filling. Effects of Heat Losses and Filling Rate Optimization, *International Journal of Hydrogen Energy*, **39**, No. 24, 2014, pp. 12701-12714.
8. De Miguel, N., Ortiz Cebolla, R., Acosta, B., Moretto, P., Harskamp, F. and Bonato, C., Compressed Hydrogen Tanks for Compressed Application: Thermal Behaviour during Cycling, *International Journal of Hydrogen Energy*, **40**, No. 19, 2015, pp. 6449-6458.
9. De Miguel, N., Acosta, B., Baraldi, D., Melideo, R., Ortiz Cebolla, R. and Moretto, P., The Role of Initial Tank Temperature on Refuelling of Compressed Hydrogen Tanks, *International Journal of Hydrogen Energy*, **41**, No. 20, 2016, pp. 8606-8615.
10. Bourgeois T., Ammouri F. and Weber M., Evaluating the Temperature inside a Tank during a Filling with Highly-pressurized Gas, *International Journal of Hydrogen Energy*, **40**, No. 35, 2015, pp. 11748-11755.
11. Bourgeois T., Brachmann T. and Barth F., Optimization of Hydrogen Vehicle Refuelling Requirements, *International Journal of Hydrogen Energy*, **42**, No. 19, 2017, pp. 13789-13809.
12. Kuroki T., Sakoda N., and Shinzato K., Dynamic Simulation for Optimal Hydrogen Refueling Method to Fuel Cell Vehicle Tanks, *International Journal of Hydrogen Energy*, **43**, No. 11, 2018, pp. 5714-5721.
13. Xiao, J.S., Bénard, P. and Chahine, R., Charge-discharge Cycle Thermodynamics for Compression Hydrogen Storage System, *International Journal of Hydrogen Energy*, **41**, No. 12, 2016, pp. 5531-5539.
14. Xiao, J.S., Bénard, P. and Chahine, R., Estimation of final hydrogen temperature from refueling parameters, *International Journal of Hydrogen Energy*, **42**, No. 11, 2017, pp. 7521-7528.
15. Xiao, J.S., Wang, X., Zhou, X., Bénard, P. and Chahine, R., A Dual Zone Thermodynamic Model for Refueling Hydrogen Vehicles, *International Journal of Hydrogen Energy*, **44**, No. 17, 2019, pp. 8780-8790.
16. Liu, J., Zheng, S.Y., Zhang Z.X., Zheng, J.Y. and Zhao, Y.Z., Numerical Study on the Fast Filling of On-bus Gaseous Hydrogen Storage Cylinder, *International Journal of Hydrogen Energy*, **45**, No. 15, 2020, pp. 9241-9251.