Bonfire Tests of High Pressure Hydrogen Storage Tanks

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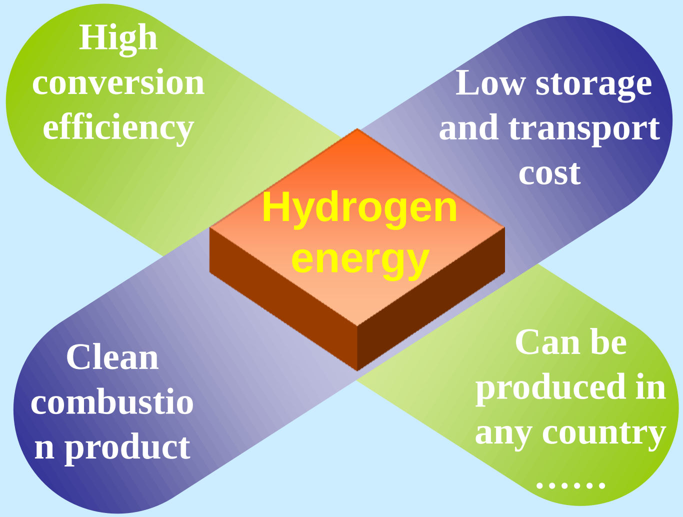
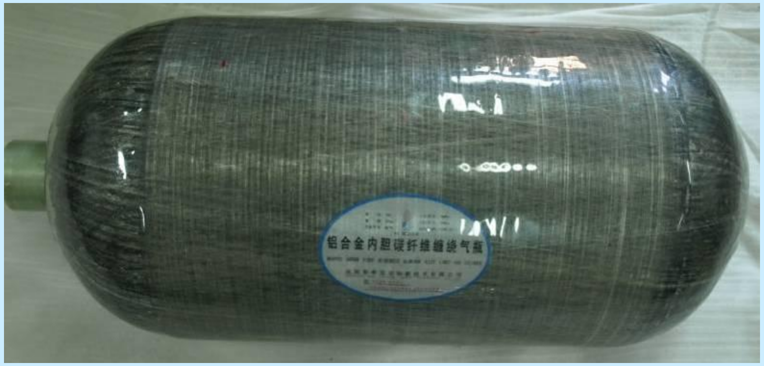
1. Introduction





Economic and safe hydrogen storage technology has been a critical issue of the popularization and the application of hydrogen fuel cell vehicles.

An Al-liner carbon-fiber/epoxy high-pressure hydrogen storage vessel is excellent in high-pressure-resistant ability, light weight and corrosion resistance.

The carbon-fiber/epoxy composite laminate is sensitive to fire and high-temperature which would degrade its mechanical properties. An explosion will probably occur when the high-pressure hydrogen storage vessel is subjected to a fire accident.

Therefore, the PRD must be installed to the onboard hydrogen storage vessels.

Issues in the conduction of bonfire test :

- Fuel type of fire source
- Fuel flow of fire source

→ **Have influence on the temperature distribution and the PRD activation time.**

Have not specified.

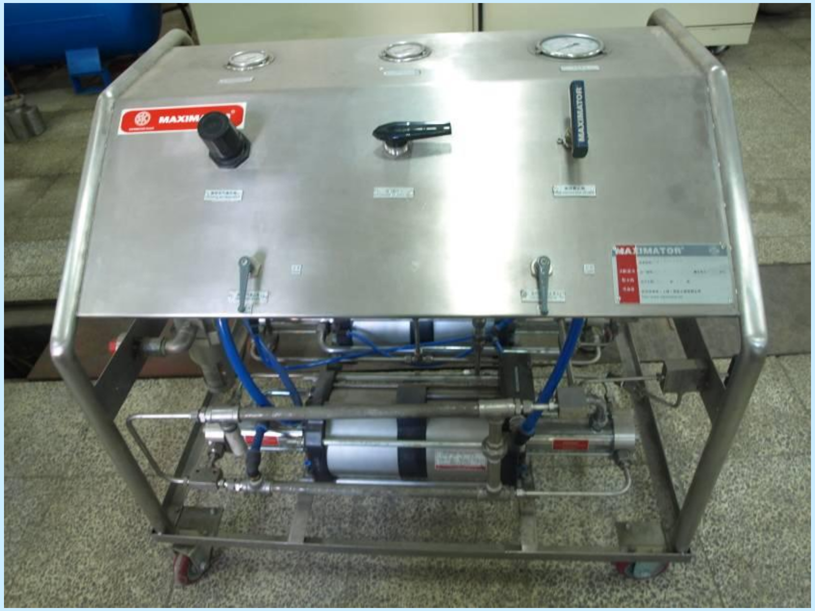
- Filling medium of the vessel

→ **For CNG vessel, the test vessel can be filled with CNG, CH_4, Air or N_2 in bonfire test.**

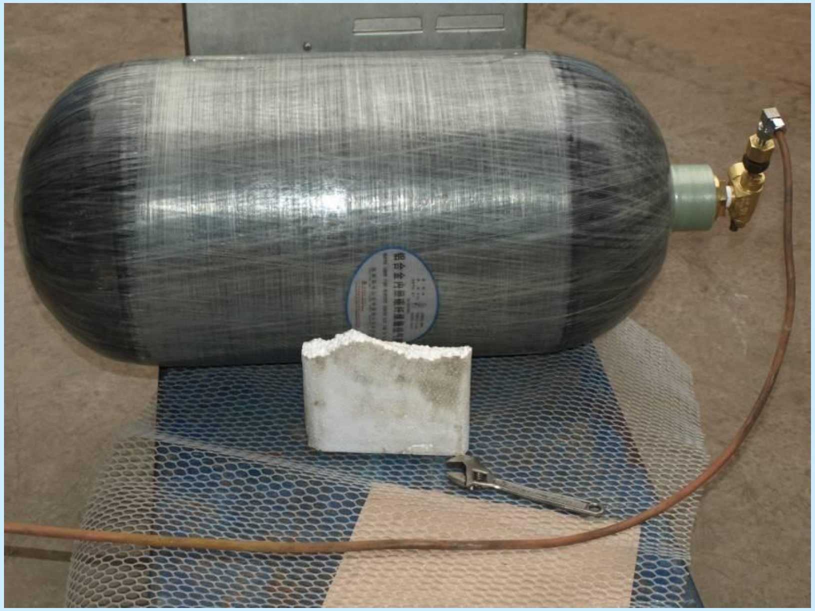
It would be more convenient and safer to use air to pressurize the vessel.

2. Experimental study

Filling of the vessel

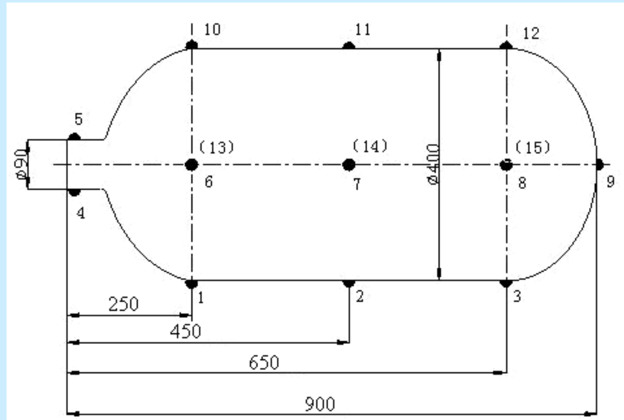


100MPa hydrogen compressor



The high-pressure hydrogen storage vessel

Schematic of thermocouples arrangement



The temperatures of the outer surface of the vessel were monitored by fifteen thermocouples (type K) located on the outer surface of the vessel. The temperature measurement of the thermocouple ranges from 0 ℃ to 1300 ℃ ± 1 ℃.

Metallic shielding **was used to prevent direct flame impingement on the PRD.**

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September 27, 2010

Process of bonfire test

Hydrogen deflagration after PRD was activated

The PRD opened after 377s and the discharged hydrogen deflagrated immediately.

Because of the front shielding, the deflagration flame jetted reversely to the head of the vessel. During the experiment, the hydrogen vented through the PRD and the vessel was not rupture.

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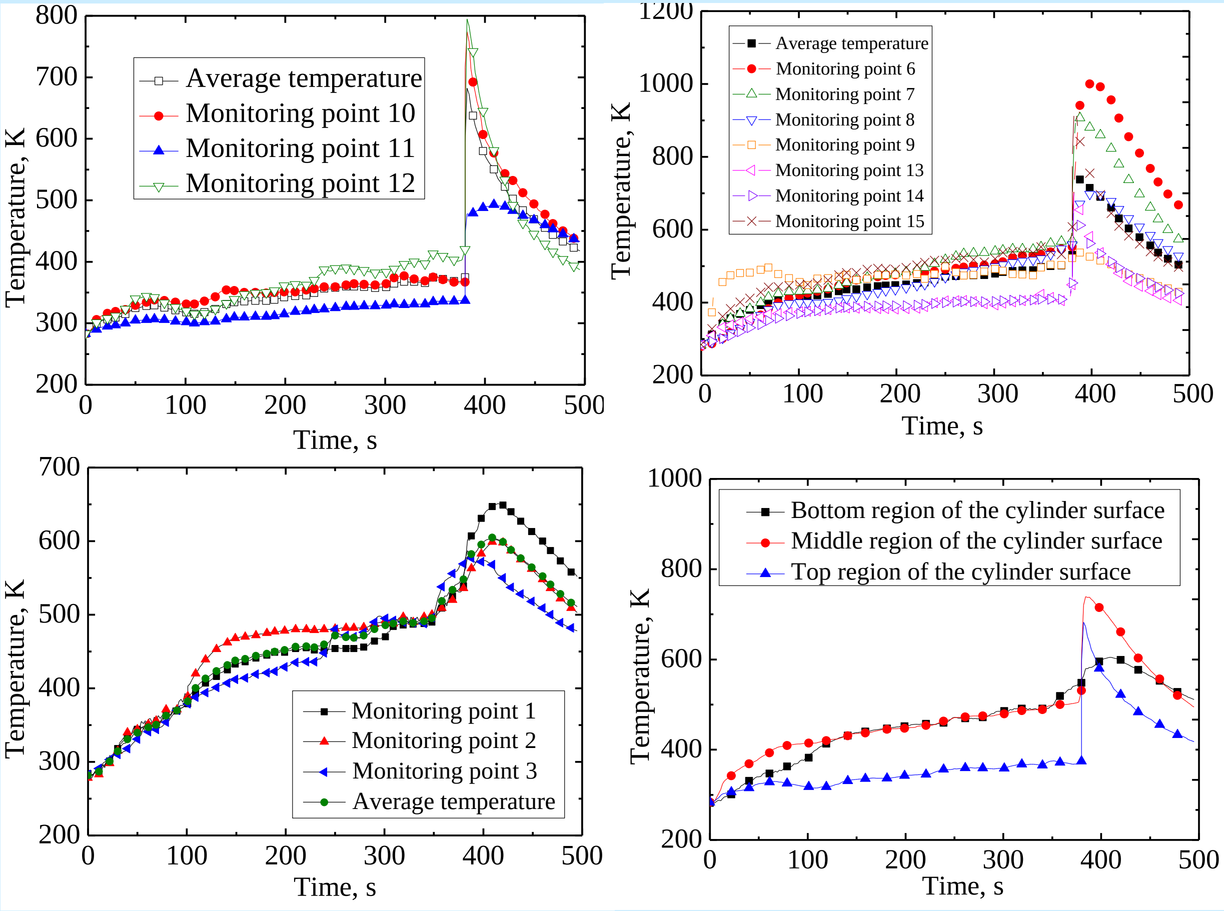
Temperatures of monitoring points at upper regionof the vessel

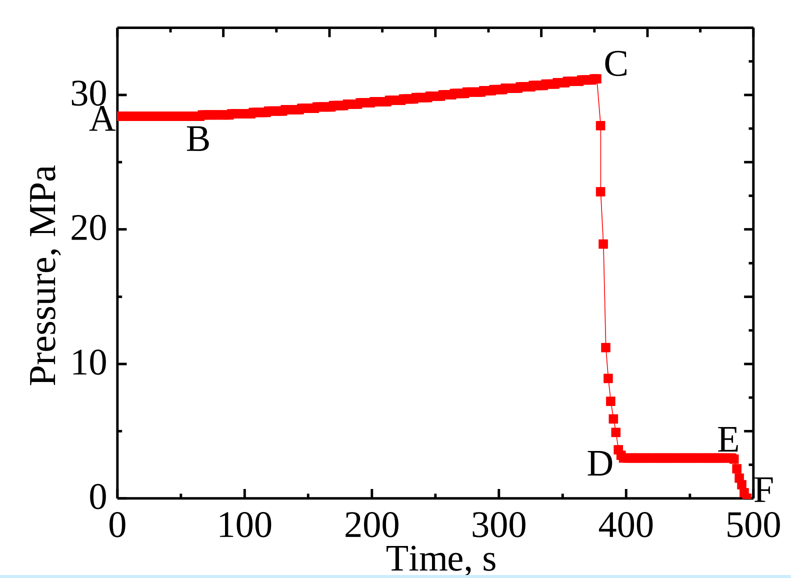
Temperatures of monitoring points at middle region of the vessel



Temperatures of monitoring points at bottom region of the vessel

Temperatures at the different regions of the vessel surface

The differences of the average temperatures between the upper and bottom regions are nearly 100 K. It indicates that the temperature distribution outside the vessel is non-axi-symmetric.



The process of ***pressure*** variation of hydrogen inside the vessel

At the first stage from A to B, there were no significant changes in the internal pressure. The thermal conductivities of composite laminates making up the vessel walls are small, the heat conducted into the internal gas was little.

From B to C, the heat conducted into the internal gas increased gradually, and thus the pressure in the vessel rose accordingly.

When the pressure reached to 31.2 MPa at 377 s, the PRD opened and the pressure in the vessel decreased dramatically. The internal pressure decreased rapidly from C to D.

Due to the interaction of the gas discharging and the rising of gas temperature, the internal pressure of the vessel decreased very slowly at the stage from D to E.

In the end, the pressure dropped quickly until the ambient pressure 0.1 MPa was reached.

3. Simulation study

- The 3D numerical model for simulating the process of the bonfire test was developed according to the bonfire experiment.
- The geometry sizes of the vessel in the model are the same as the vessel used in the bonfire test.

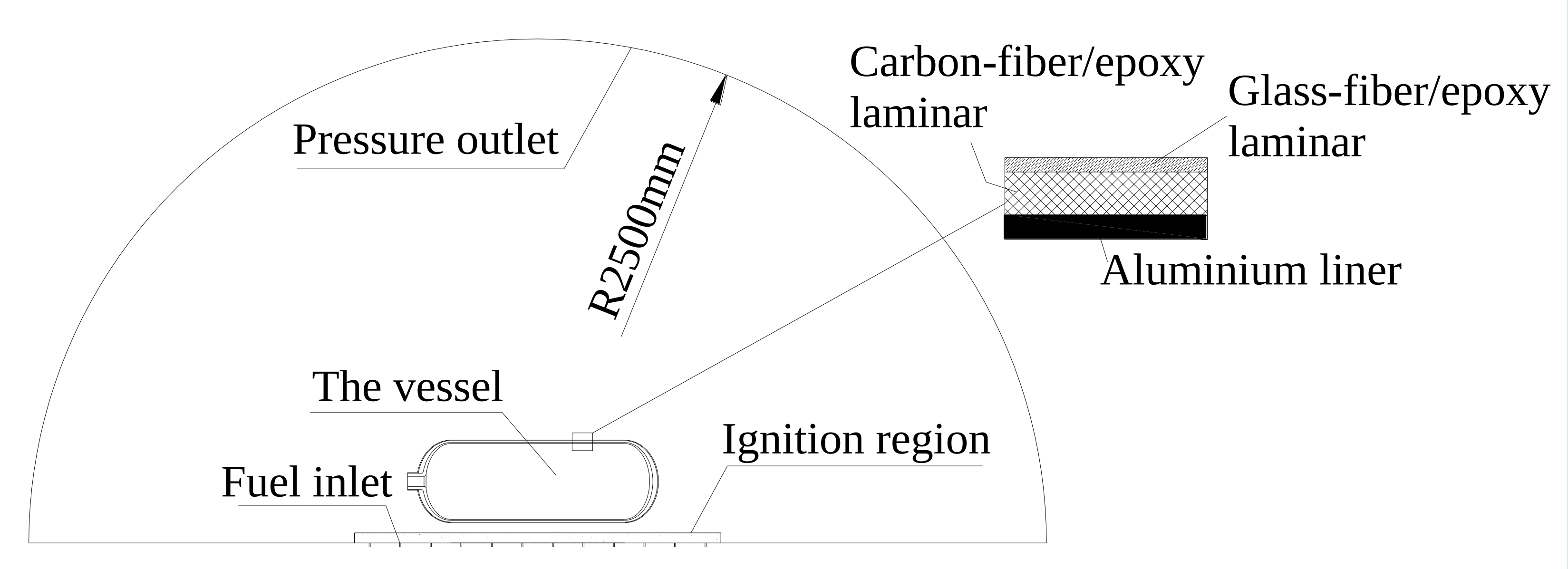
Basic assumptions:

(1) As the three laminates making up the vessel wall attach tightly, the temperatures between adjacent interfaces in the vessel wall vary continuously.

(2) In the bonfire test, metallic shielding was used to prevent direct flame impingement on the PRD, and consequently, the fuel inlet under the PRD is canceled in the model.

(3) The material damage of the vessel wall was slight in the experiment. In this model, the structure of the vessel wall is assumed to be stable.

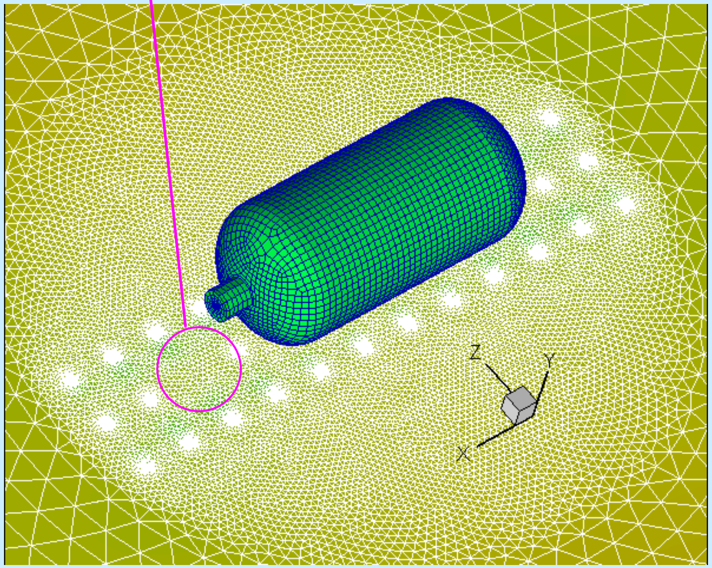
(4) The fuel in the model is assumed to combust completely.



Schematic of the calculation region

- **The whole calculation region of the model is a hemispheroid with a diameter of 5,000 mm, and the pressure boundary is applied to be outlet.**

The fuel inlet under the PRD is canceled in the model.



Partial view of the computational grid structure

- Hexahedral structured grid is adopted to mesh the internal gas region and the wall of the straight section. For the other parts, unstructured grid is used.
- The grids around the fuel inlet region, the wall of the vessel and the fuel combustion region are refined.
- The total grid number of the model is 343,481 and the node number is 92,120.

① **Species transport and finite-rate chemistry model is employed in combustion simulation while the turbulence-chemistry interaction model takes the Eddy-Dissipation model.**

② **Single-step global forward reaction is adopted to simulate the combustion of fuel gas with air. And the calculation of the unsteady governing conditions is based on the finite volume method.**

③ **Renormalization-group (RNG), $k-\varepsilon$ model is adopted to simulate the turbulence model**

Governing equations

- ✓ **The equation of mass conservation**

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho u_j}{\partial x_j} = 0$$

- ✓ **The equation of momentum conservation**

$$\frac{\partial (\rho u_i)}{\partial t} + \frac{\partial (\rho u_i u_j)}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}[\mu(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i})] - \frac{2}{3}\frac{\partial}{\partial x_i}\left[\delta_{ij}\left(\rho k + \mu \frac{\partial u_k}{\partial x_k}\right)\right]$$

- ✓ **The equation of energy conservation**

$$\frac{\partial}{\partial t}(\rho E) + \frac{\partial}{\partial x_i}\left[u_i(\rho E + p)\right] = \frac{\partial}{\partial x_j}\left(k_{\text{eff}}\frac{\partial T}{\partial x_j} + u_i(\tau_{ij})_{\text{eff}}\right) + S_h$$

- **Renormalization-group (RNG), $k-\varepsilon$ model is adopted to simulate the turbulence model. The turbulence kinetic energy k and the dissipation rate ε can be obtained from the following transport equations:**

$$\frac{\partial(\rho k)}{\partial t}+\frac{\partial(\rho u_i k)}{\partial x_i}=\frac{\partial}{\partial x_j}\left(\frac{\mu_{\text{eff}}}{\sigma_k}\frac{\partial k}{\partial x_j}\right)+G_k-\rho\varepsilon$$

$$\frac{\partial(\rho\varepsilon)}{\partial t}+\frac{\partial(\rho u_i\varepsilon)}{\partial x_i}=\frac{\partial}{\partial x_j}\left(\frac{\mu_{\text{eff}}}{\sigma_\varepsilon}\frac{\partial \varepsilon}{\partial x_j}\right)+\frac{\varepsilon}{k}(C_{\varepsilon 1}G_k-C_{\varepsilon 2}\rho\varepsilon)$$

- **The equation of species transport and diffusion is expressed by the following form:**

$$\frac{\partial}{\partial t}\left(\rho Y_i\right)+\nabla\cdot\left(\rho\vec{v}Y_i\right)=-\nabla\cdot\vec{J}_i+R_i$$

✓ **For the turbulent flow formed by the jet of fuel gas, the mass diffusion rate of species *i* is obtained by the following equation:**

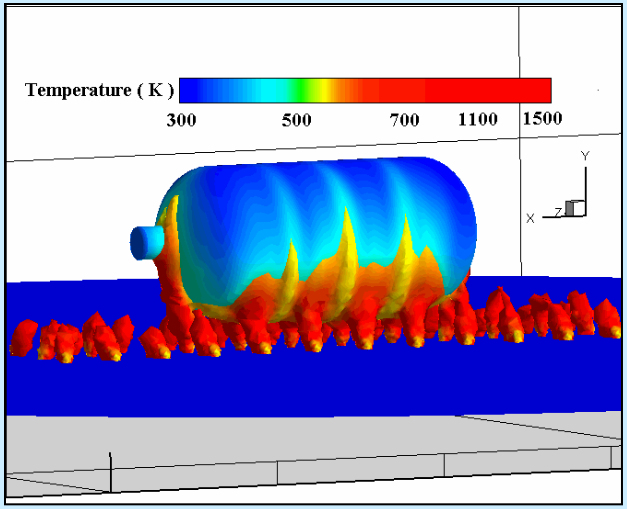
$$\vec{J}_i = -\left(\rho D_{i,m} + \frac{\mu_t}{S_t}\right)\nabla Y_i$$

✓ **The net rate of generation of species *i* due to reaction *r*,** $R_{i,r}$ **, is given by the smaller one of the following two rates:**

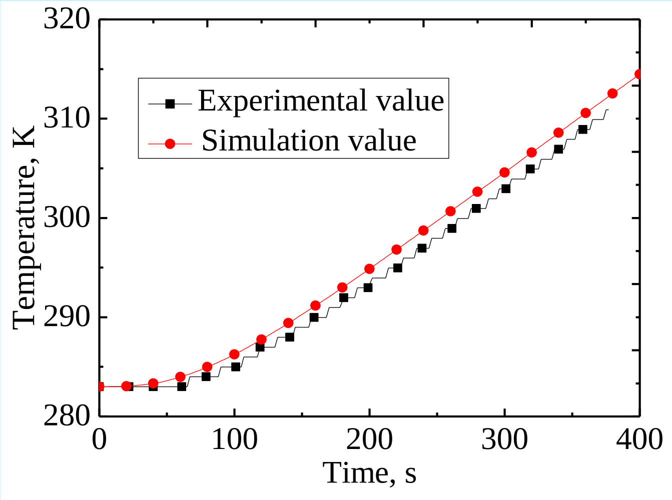
$$R_{i,r} = v'_{i,r} M_{w,i} A\rho \frac{\omega}{k} \min_{\mathrm{R}}\left(\frac{Y_{\mathrm{R}}}{v'_{\mathrm{R},r} M_{w,\mathrm{R}}}\right)$$

$$R_{i,r} = v'_{i,r} M_{w,i} \mathrm{AB}\rho \frac{\omega}{k} \frac{\sum_P Y_P}{\sum_j^N v''_{j,r} M_{w,j}}$$

Validation of the model



Local view of the 3D fire flame



Comparison of temperature rising between the simulation and experimental results

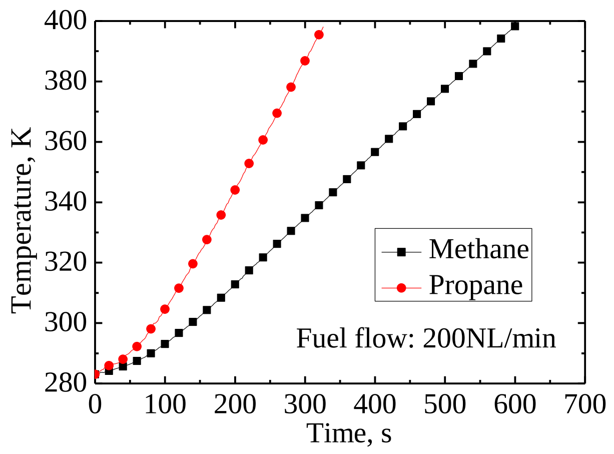
The parameters of the model are based on the experiment: the filling medium of the vessel is hydrogen, the initial temperature is 283 K, the filling pressure is 28.4 MPa and the fuel gas is compressed natural gas with a fuel flow of 70 NL/min.

The model was employed to analyze the influences of test parameters on the temperature rising, such as *fuel type, fuel flow* and *filling medium*.

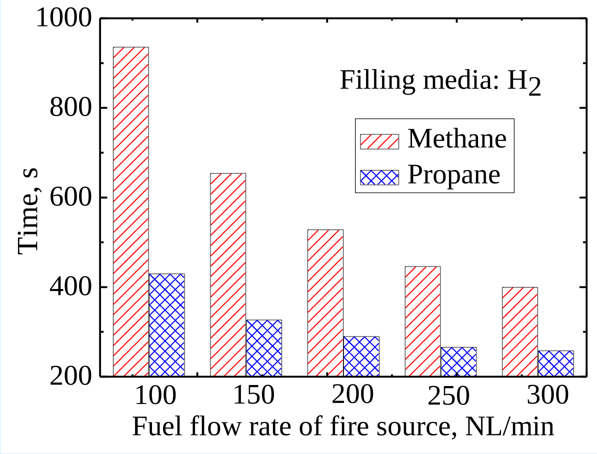
Influence of fuel types

Any fuel may be used for the fire source to maintain the specifued fire conditions.

Take the commonly used fuel will be convenient. *The natrual gas* (mainly consists of methane) and *the propane gas* are taken into account.



The processes of temperature rising of hydrogen gas with different fuels

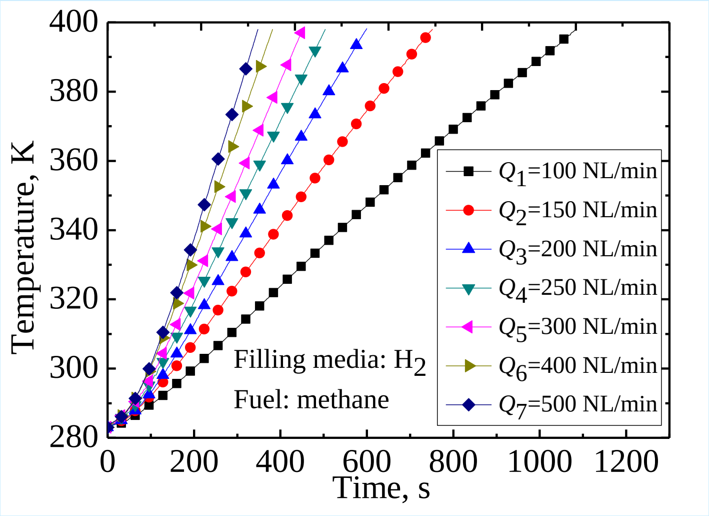


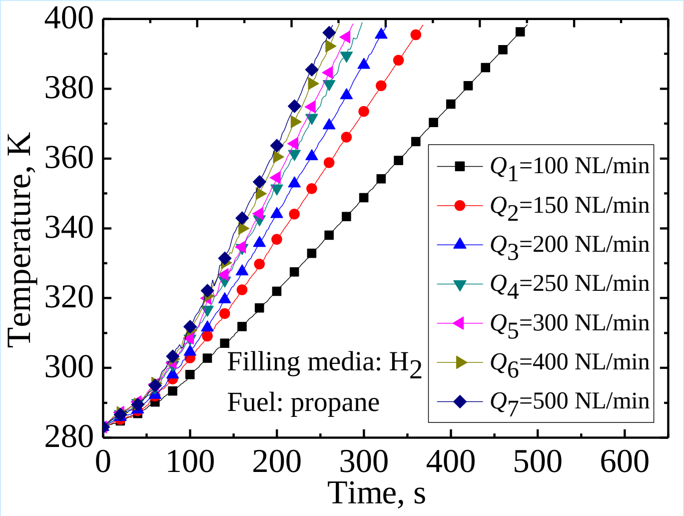
The time when the PRD activated (set at T=383K) with different fuels

The rate of temperature rising with methane as fuel is much smaller than that with propane.

The combustion heat generated by propane gas is much higher than that by methane with the same flow rate, and therefore, the energy transferred to the internal gas by propane is much larger than that by methane.

Influence of the fuel flow





Temperature variations of internal gas with time under different fuel flows

The change in the rate of temperature rising is small when the fuel flow is larger than 200 NL/min. Assuming that the fire resistance time of the high-pressure vessel is 6 min and the PRD activation temperature is 383 K, the flow should be larger than 400 NL/min if methane gas is used as fuel or larger than 150 NL/min when propane gas is applied.

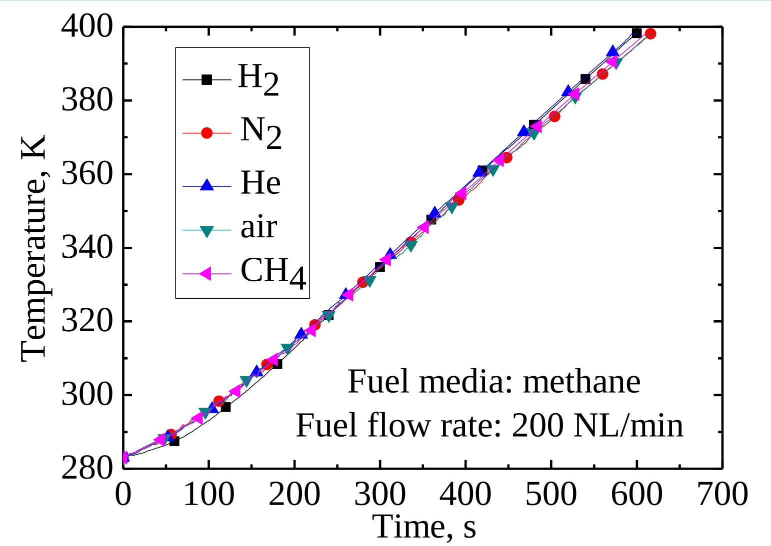
Influence of the filling media

Metallic shielding is used to prevent direct flame impingement on the PRD. The PRD is permanently connected to the interior of the valve. Its activation will be greatly influenced by the temperature of the filling gas.

(1) Effects on the temperature rising of filling gas

The filling medium has little influence on the temperature rising.

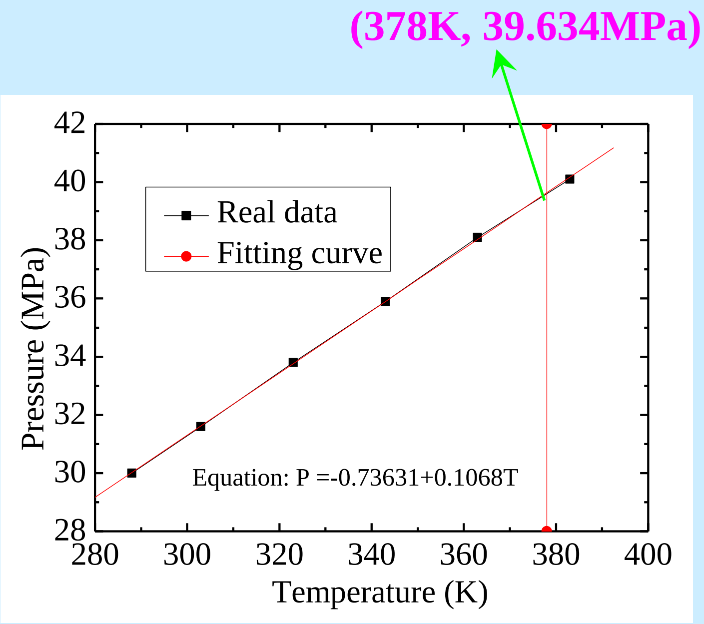
The rate of temperature rising with air as filling medium is almost the same as that with hydrogen.



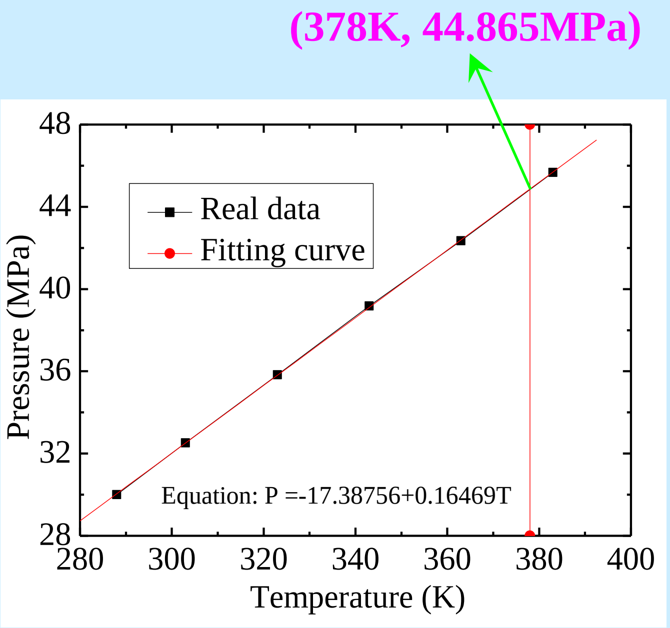
Temperature rising with different filling media

(2) Effects on the pressure rising of filling gas

According to the National Institute of Standards and Technology (NIST) chemistry database:

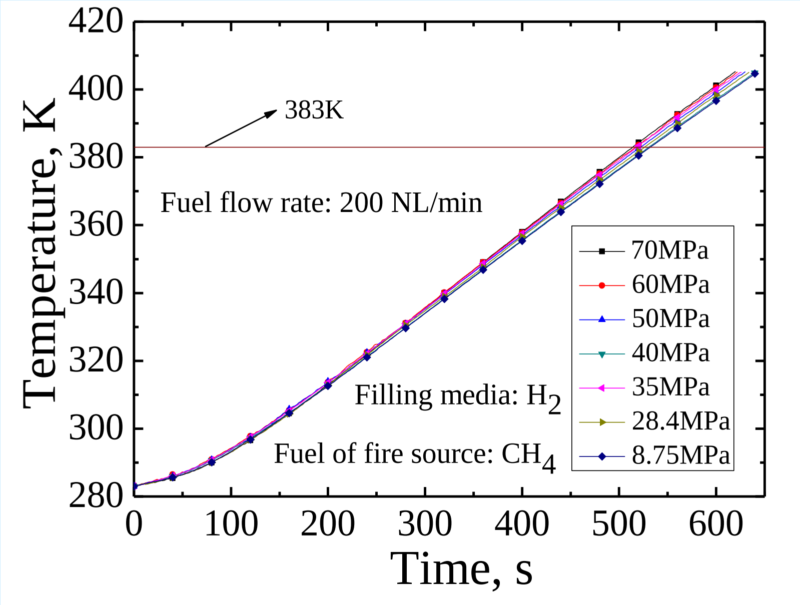


Gas state equation of ***hydrogen*** at constant density



Gas state equation of ***air*** at constant density

(3) Effects of the filling pressure



The influence of filling pressure on the temperature rising is tiny.

According to the studies on the influences of the filling media and filling pressure on the temperature rising, it is feasible to use air as substitutive filling gas in bonfire test of hydrogen storage vessels while an appropriate filling pressure is chosen.

4. Conclusions

(1) The effect of fuel type on the temperature rising is significant. The rate of the temperature rising increases as the fuel flow increases.

(2) The filling medium has little influence on the rate of temperature rising.

(3) Appropriate fuel flow rates are proposed when using different fuels.

(4) It is feasible to use air as substitutive filling gas in bonfire test of hydrogen storage vessels .

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~Thank you~