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Development and Test of Metallic Solid-State Hydrogen Storage Module for Hydrogen Energy Locomotive Application

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Abstract

The hydrogen storage amount has decisive impact on the performance of hydrogen locomotives. Metallic solid-state hydrogen storage has the advantages of high hydrogen density, therefore has good application prospect in hydrogen locomotives. In this paper, a metallic solid-state hydrogen storage module is developed with TiMn alloy, of which the volume hydrogen density reaches 30.4 g/L. The hydrogen supply capacity of the module reaches 10 kg/h, qualified for 150 kW hydrogen fuel cell. By using the exhaust heat from the hydrogen fuel cell to heat the metallic solid-state hydrogen storage module, 25.14% of the exhaust heat is recycled, leading to high energy efficiency of the integrated system. The research result of this paper puts forward with a solution for the development of hydrogen locomotives with large hydrogen storage amount and long running distance.

Keywords: locomotive, hydrogen energy, metallic solid-state hydrogen storage, system integration, volume hydrogen density, thermal management.

1 Introduction

Driven by the climate neutral strategy, the railway transportation industry is transferring to green energy and zero carbon emission propulsion technologies. With the advantages of zero emission, environmentally friendly and high efficiency, hydrogen energy is getting increasing application in rail transit vehicles[1, 2]. The manufacturers across the world has developed hydrogen energy locomotives, multiple units, trams and engineering vehicles and put into application[3~5].

The on-board hydrogen storage amount has decisive impact on the running mileage of rail transit vehicles. Therefore high hydrogen storage density becomes an essential requirement for the hydrogen storage system[6]. However, the currently widely used high-pressure gaseous hydrogen storage, of which the pressure is 35 MPa or 70 MPa, has limited volume hydrogen storage density. So, to increase the hydrogen storage density has become one of the R&D topic for hydrogen energy rail transit vehicles.

Based on the chemical reaction between the hydrogen storage alloys and H_2, the metallic solid-state hydrogen storage has the advantages of high volume hydrogen storage density, low pressure and low safety risk, making it a promising technology for hydrogen energy rail transit vehicles, especially the hydrogen locomotives[7].

In this paper, a high-capacity metallic solid-state hydrogen storage module is developed and tested. Based on the thermodynamic property of the hydrogen storage alloy, the metallic solid-state hydrogen storage module is integrated with the hydrogen fuel cell system and tested. The hydrogen storage and supply capacity is tested and evaluated. Based on the results, a hydrogen energy locomotive concept is developed to demonstrate the application feasibility of metallic solid-state hydrogen storage technology. The results indicate that metallic solid-state is a promising solution toward higher hydrogen storage amount for locomotives.

2 Development of metallic solid-state hydrogen storage module

There are many hydrogen storage alloys, including Ti-based, Mg-based and rear earth-based alloys, of which the parameters are as listed in Table. 1. From the perspective of compatibility with hydrogen fuel cell system and locomotive platform, the technical requirements for hydrogen storage materials include high hydrogen storage density, appropriate hydrogen release temperature and pressure (>0.1 MPa) and acceptable cost. Therefore, Mg-based alloys are excludes for low hydrogen release pressure and hydrogen release temperature above 270 ℃, making it very difficult to heat the alloy with on-board equipment. The RE-based alloys are excluded for its high cost. On the other hand, the Ti-based alloys shows the advantages of high hydrogen storage density and appropriate hydrogen release pressure. Moreover, the hydrogen release temperature of Ti-based alloys is between 60~70 ℃, in the range of proton exchange hydrogen fuel cell (PEMFC) working temperature, making it possible to heat the alloy with the exhaust heat from the PEMFC. As a result, the TiMn alloy is used in this research.

Table. 1 The parameters of hydrogen storage alloys

Hydrogen storage alloy	Volume hydrogen storage density (g/L)	Mass hydrogen storage density (wt%)	Hydrogen release temperature (℃)	Hydrogen release pressure (MPa)
RE based (LaNi5)	42.8	1.38	22	0.1
RE based (La2Ni7)	62.0	2.00	298	0.2
Ti based (TiFe)	83.7	1.89	60	0.2
Ti based (TiMn)	60~80	1.8	70	0.2
Mg based (Mg)	132.4	7.60	282	0.1
Mg based (Mg2Ni)	111.6	3.60	275	0.1

Based on TiMn alloy, a metallic solid-state hydrogen storage module is developed, of which the structure is shown in Fig. 1. The TiMn alloy powder is filled in the stainless steel tube, with one end sealed and the other end a hydrogen valve installed, resulting in a hydrogen storage unit. 28 units in total are fixed with verticle bulkheads, which are contained in the water jacket consisting of the end plates and lateral plates. The hydrogen valves are connected with hydrogen pipes and a master valve to control the hydrogen release process. Two water pipe connectors are installed on the end plate for the flow of heating fluid.

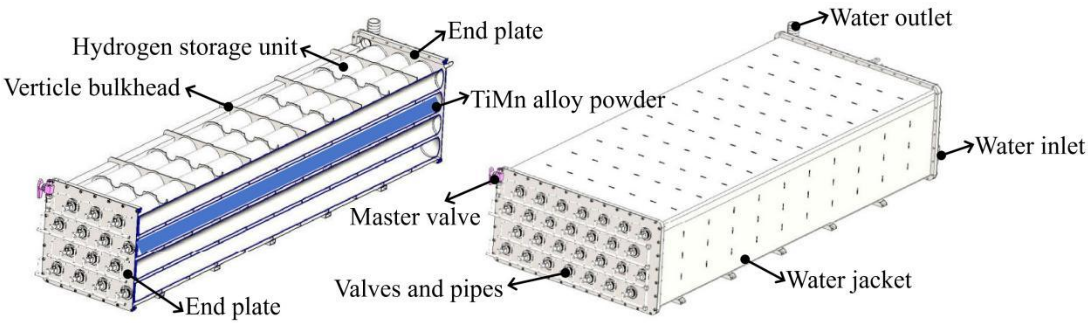


Fig. 1 The structure of the metallic solid-state hydrogen storage module

3 Integration of metallic solid-state hydrogen storage module and hydrogen fuel cell

3.1 Integration system configuration

Based on the compatibility between the hydrogen release temperature of TiMn alloy and the PEMFC exhaust heat temperature, this research puts forward a high efficiency integration configuration of metallic solid-state hydrogen storage module and hydrogen fuel cell, as shown in Fig. 2. The key equipment is a heat exchanger. In the hydrogen fuel cell cooling fluid loop (the red line), the fluid flow out of the fuel cell stack with temperature between 60~80 ℃, and then flow through the heat exchanger. In the metallic solid-state hydrogen storage heating fluid loop (the green line), the fluid flow through the heat exchanger, got heated and then flow into the metallic solid-state hydrogen storage module. With this configuration, the TiMn hydrogen storage alloy is heated by the exhaust heat from the fuel cell stack. The hydrogen released is supplied to the fuel cell stack.

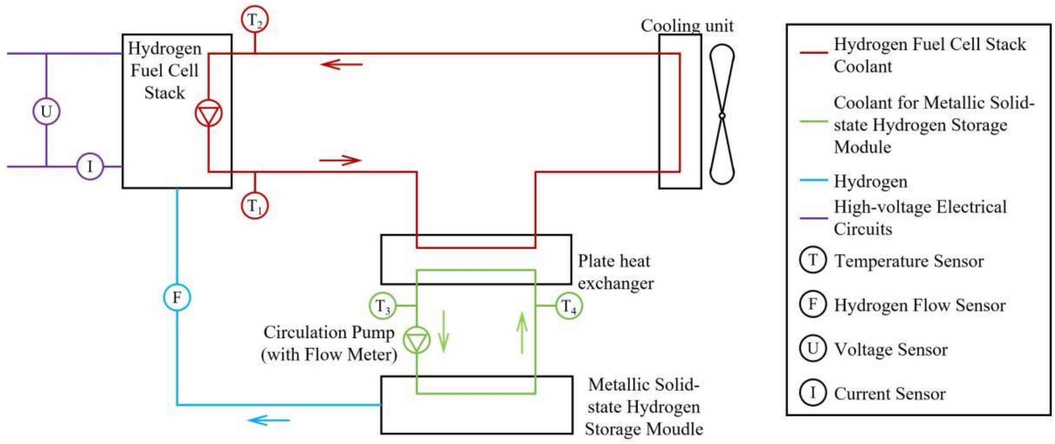
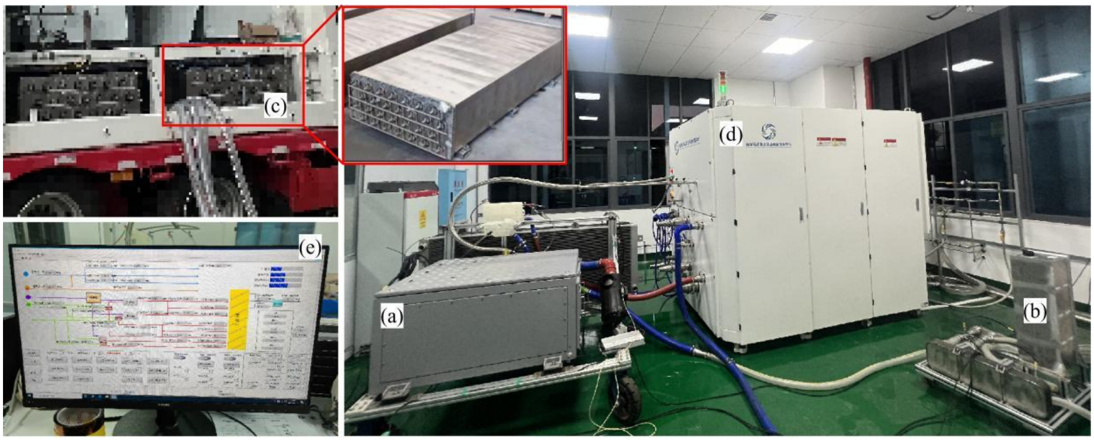


Fig. 2 System configuration of metallic solid-state hydrogen storage module integrated with hydrogen fuel cell

Various sensors, including temperature, flow rate, current and voltage are implemented to monitor the working condition of the system. The system is tested with a fuel cell system test bench, as shown in Fig. X.



(a) Hydrogen fuel cell, (b) Plate heat exchanger, (c) Metallic solid-state hydrogen storage module, (d) The test bench, (e) Central control panel

Fig. 3 The integrated system on the test bench

3.2 Data analysis method

The exhaust heat power of the hydrogen fuel cell and the heat absorption power of the metallic solid-state hydrogen storage module are calculated as equation (1):

$$P = Cf\Delta T = Cf(T_{out} - T_{in}) \tag{1}$$

Where P is the heat generating power of hydrogen fuel cell or the heat absorption power of metallic solid-state hydrogen storage module, kW. C is the specific heat of the fluid, and the value is 4.18 J/(g. ℃). f is the flow rate of the fluid, m^3/h. T_{out} and T_{in} is the temperature at the inlet and outlet of the heat exchanger.

The utilization ratio of exhaust heat from the hydrogen fuel cell is calculated according to equation (2):

$$\eta = \int P_{HS}\, dt \div \int P_{FC}\, dt \tag{2}$$

Where P_{HS} is the heat absorption power of the metallic solid-state hydrogen storage module, and P_{FC} is the heat generation power of the fuel cell, kW. t is the experiment time, s.

4 Result and discussion

4.1 Hydrogen storage performance

For the metallic solid-state hydrogen storage module as shwon in Fig. 4(a), the dimension is 2400 mm (Length)×980 mm (Width)×495 mm (Height), and the mass (before refueling) is 2900 kg. The maximum hydrogen storage amount is 35.36 kg, therefore the volume hydrogen storage density is 30.4 g/L. For comparison, there are two hydrogen locomotives with high-pressure gaseous hydrogen storage. One implement 450 L large-size tanks with 35 MPa nominal pressure, as shown in Fig. 4(b), the volume hydrogen storage density is 8.8 g/L. The other on implement tanks with 70 MPa nominal pressure, as shown in Fig. 4(c), the volume hydrogen storage density is 10.6 g/L. The results demonstrate that with metallic solid-state hydrogen storage, the volume density is 3 to 4 times of that of high-pressure gaseous hydrogen storage.

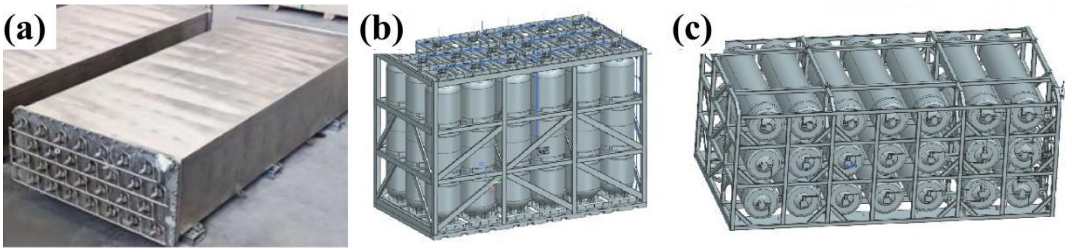


Fig. 4 (a) Metallic solid-state hydrogen storage module, (b) 35 MPa and (c) 70 MPa gaseous hydrogen storage module

4.2 Hydrogen supply performance

Test results of the hydrogen supply performance from the TiMn hydrogen storage module is as illustrated in Fig. 5. The water temperature is key to the hydrogen release behavior of the module. Three temperature steps, i.e. 40 ℃,, 50 ℃ and 55 ℃ are set during the test. Start with 40 ℃, the H_2 flow rate climbs to 9~12 kg/h, staying stable for about 60 minutes, which then decreases to below 2.5 kg/h. Then with the increase of water temperature, the H_2 flow rate increases to 9~11 kg/h for about 30 minutes at

50 ℃, and 8~10 kg/h for about 20 minutes at 55 ℃. The H_2 pressure shows synchronous and similar variation pattern, and the pressure is about 0.1 MPa. It is supposed to be influenced by the temperature difference between the water and the TiMn alloy. With the heat transfer from the water to the TiMn alloy, the TiMn alloy releases hydrogen, meanwhile the temperature of the TiMn alloy increases. As a result, the temperature difference between the water and the TiMn alloy decreases, leading to decreased heat transfer efficiency and therefore decreased hydrogen release rate. It is concluded that high heating fluid temperature is beneficial to the H_2 release process.

The test result indicates that the metallic solid-state hydrogen storage module has a H_2 supply capacity of around 10 kg/h, which is able to support the operation of 150 kW hydrogen fuel cell system.

It should be noted that the metallic solid-state hydrogen storage module is not fully refueled at the beginning of the test, therefore the total H_2 release mass stopped at 20 kg.

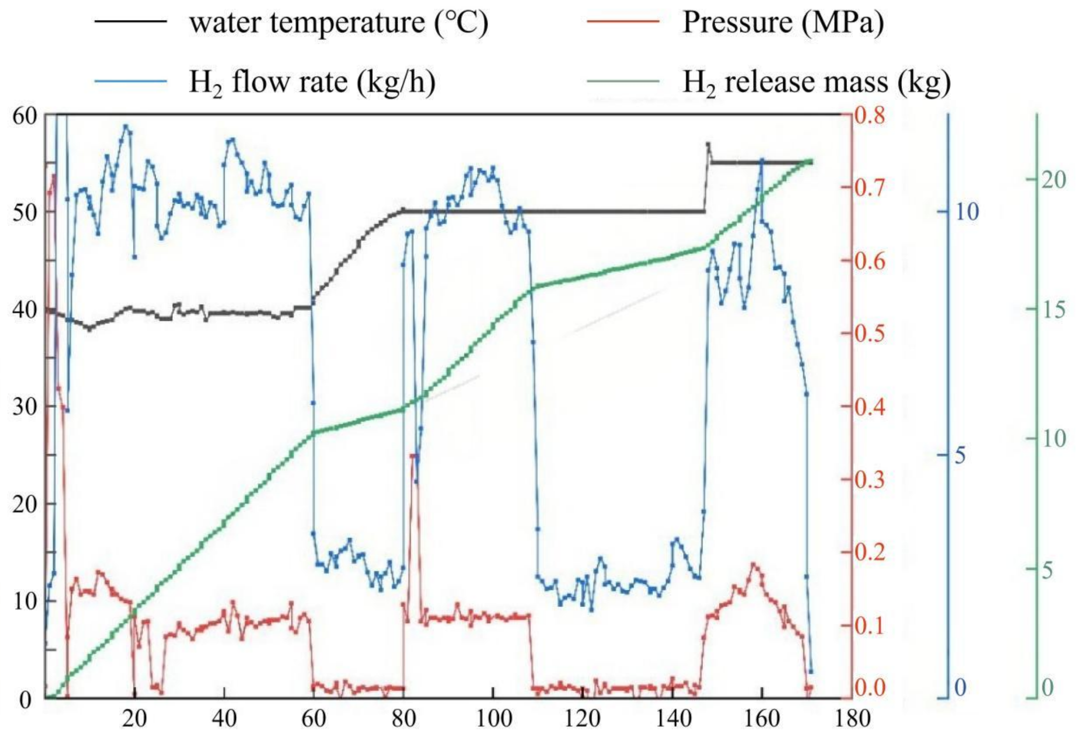


Fig. 5 The hydrogen supply performance test result of the metallic solid-stage hydrogen storage module

4.3 Combined operation of hydrogen fuel cell and metallic solid-state hydrogen storage module

During the test process, the operating status of the system is stable. As shown in Fig. 6, the hydrogen flow rate of the metallic solid-state hydrogen storage module is about 520 L/min, i.e. about 0.77 g/s. The output voltage of the fuel cell stack is about 460 V, and the output current is DC 113~114 V, the output power of the fuel cell stack is about 52 kW.

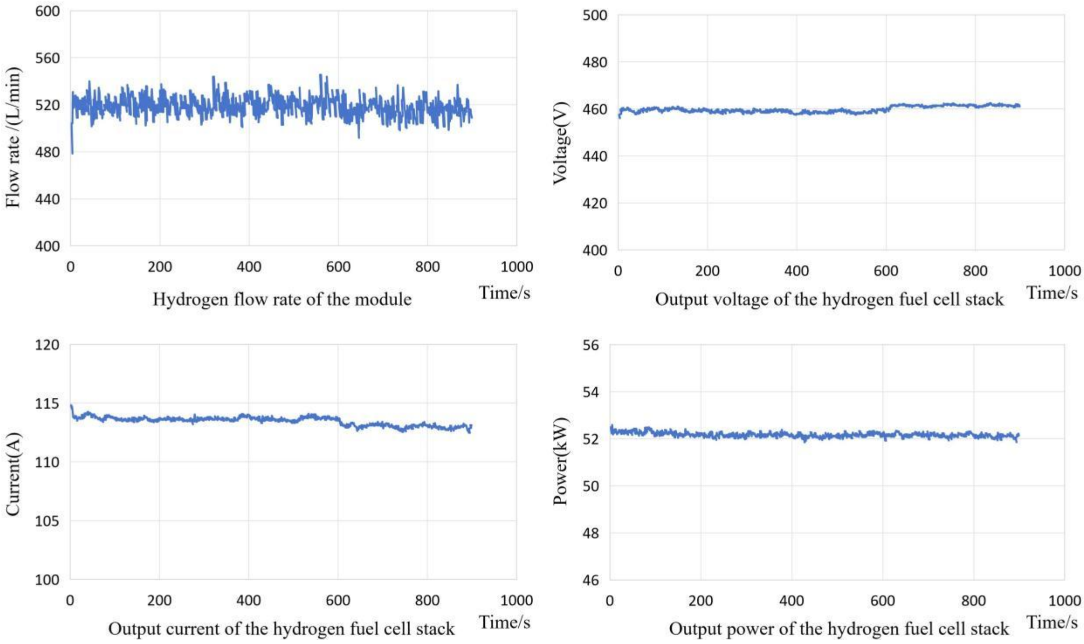


Fig. 6 The operating status of the metallic solid-state hydrogen storage module and the hydrogen fuel cell stack

The operating status of the thermal fluid loops is shown in Fig. 7. For the cooling fluid of the hydrogen fuel cell stack, the inlet temperature (T_2) is about 50 ℃, and the outlet temperature (T_1) is about 60 ℃, the temperature difference is about 10 ℃. The fluid flow rate fluctuates between 0.3 to 1.9 m^3/h. The exhaust heat power of the fuel cell stack is between 51 to 61 kW, the total heat generated during the test is 51.12 MJ.

For the cooling fluid of the metallic solid-state hydrogen storage module, the inlet temperature (T_3) increases from 40.5 ℃ at the beginning of the test to 51 ℃ at the end of the test, while the outlet temperature (T_4) increases from 38.5 ℃ to 49.5 ℃. The temperature difference is between 1 to 2.5 ℃. The fluid flow rate fluctuates between 0.3 to 1.9 m^3/h. The heat absorption power by the hydrogen storage module is between 9 to 21 kW, the total heat absorbed during the test is 12.85 MJ. The total hydrogen released is 690.86 g, and the heat absorption ratio of the hydrogen release process is 18.60 kJ/g H_2. The utilization ratio of the exhaust heat from fuel cell stack is 25.14%.

The test result demonstrates that the exhaust heat generated by the fuel cell stack is capable of providing the heat for the metallic solid-state hydrogen storage module to release H_2, therefore eliminate the need for a heating equipment. Furthermore, with the metallic solid-state hydrogen storage module absorbing 25% of the exhaust heat from the fuel cell, the required heat dissipation capability of the heat radiator of fuel cell is decreased proportionally, resulting in reduced energy consumption of the heat radiator and higher efficiency of the fuel cell system.

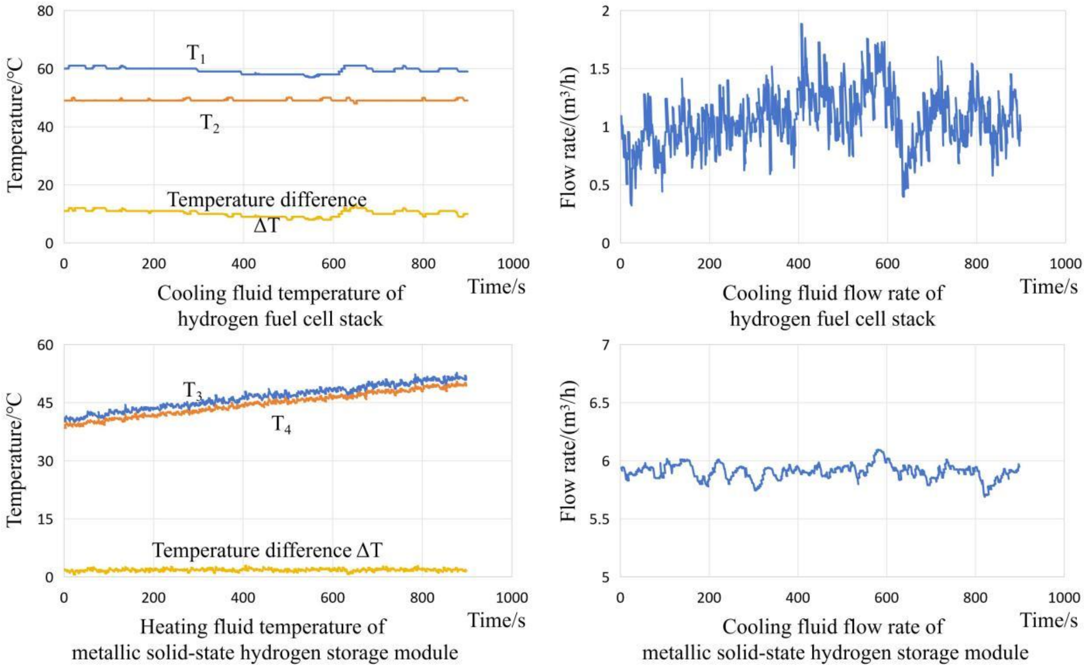


Fig. 7 The statue of the thermal management fluid of the metallic solid-state hydrogen storage module and the hydrogen fuel cell stack

5 Application concept of metallic solid-state hydrogen storage for locomotive

Based on the metallic solid-state hydrogen storage module, and based on the hydrogen energy locomotive platform, which is originally designed to have a gaseous hydrogen storage system, a application concept is developed. The gaseous hydrogen storage system is replaced with metallic solid-state hydrogen storage system, which consists of 9 hydrogen storage modules, as shown in Fig. 8. The total hydrogen storage amount is estimated to reach more than 300 kg, making it capable of generating electricity of about 4500 kWh.

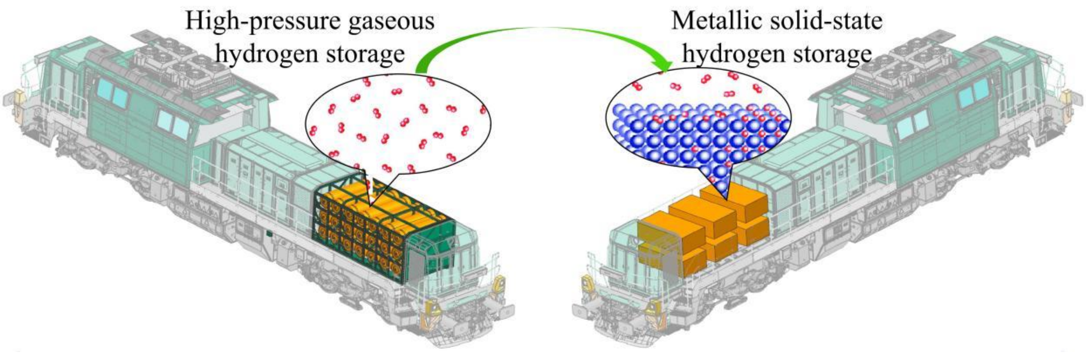


Fig. 8 The application concept of metallic solid-state hydrogen storage on a locomotive platform

6 Conclusion

In this paper, a metallic solid-state hydrogen storage module is developed and tested for its hydrogen supply performance to hydrogen fuel cell. The conclusion are as following.

(1) Metallic solid-state hydrogen storage with TiMn alloy has the advantage of high volume density, which reaches 30.4 g/L, 3 to 4 times of that of gaseous hydrogen storage module.

(2) The hydrogen supply capacity of the hydrogen storage module reaches10 kg/h, able to support the stable operation of 150 kW hydrogen fuel cell.

(3) By using the exhaust heat from the hydrogen fuel cell as heat source for the hydrogen release process of the metallic solid-state hydrogen storage module, the integrated system has the advantage of high energy efficiency. The exhaust heat utilization ratio reaches 25.14%.

(4) The metallic solid-state hydrogen storage technique is promising for application for large hydrogen storage amount and long running distance hydrogen energy locomotives.

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