THERMAL BALANCE IN FUEL CELL VEHICLES WITH LIQUID HYDROGEN UTILISATION

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ABSTRACT

Hydrogen storage and its efficiency is one of the key challenges, which has been developed in line with the popularity of the fuel cell systems. However, fuel cells operation is linked with intensive heat release, which should be utilised by the cooling system to prevent membrane damage. With on-board cooling system, the overall efficiency of the vehicle decreases further. This paper provides design of a novel system to utilise heat of the fuel cells, drivetrain elements and ventilation system to vaporize liquid hydrogen and reach higher efficiency of the system with cooling system capacity decrease.

Keywords: Fuel Cells, Liquid Hydrogen, Thermal Balance

INTRODUCTION

Hydrogen fuel cells (FC) has been seen as one of the balanced solution for electric vehicles (EVs), including cars and rail-based systems due to its refuelling time, energy density and self-discharge rate in comparison with batteries and capacitors [1]. The key challenges of FC EVs are storage weight and size, reliability concerns regarding leakages and heat utilisation from the FC due to its efficiency [2].

There have been several solutions developed to meet certain technical objectives of the storage. Absorbent-based canisters prevent leakages, but have excessive mass, in comparison with alternatives and it requires very high purity of the hydrogen. Compressed gas bottles are easy to refuel and have relatively low weight, but their leakage characteristics prevent their application for long-term storage solutions. One of the alternatives can be seen in the cryogenic compressed hydrogen systems, however, storage cost and manufacturing process are very expensive [2, 3].

Alternative solution is to store hydrogen in liquid form [4]. This helps to reduce leaks in comparison with gaseous storage systems, and doesn't require complex expensive canisters to prevent high pressure explosions. Manufacturing process is not cheap, as for the compressed gas, however, it has comparable cost with the cryogenic compressed gas production. Considering better technical performance, it provides balanced solution for the FC EV. Operation of liquid storage requires additional system to be put in EV – evaporating and heating system for the hydrogen. Heating system should increase temperature of the gas to meet requirements of the FC and its efficiency range [4,5]. Overall, hydrogen storage systems have been combined in Figure 1.

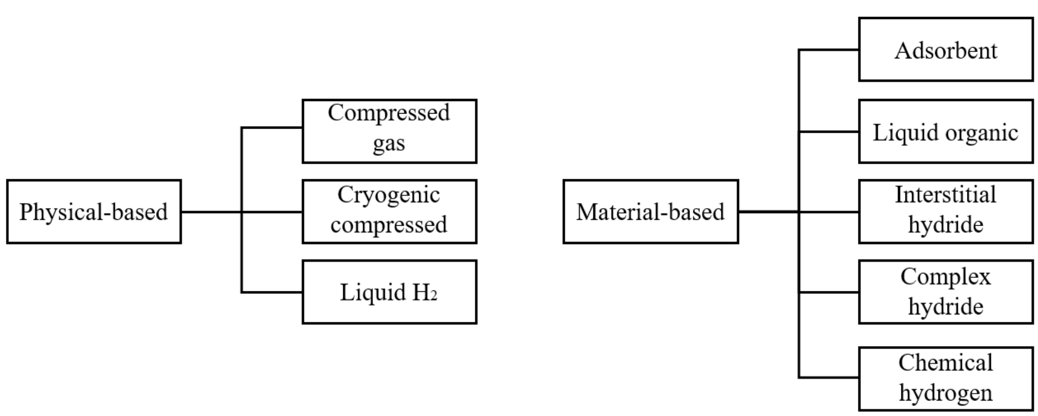

Figure 1. Hydrogen Storage Technologies

Another issue with FC EV is thermal management in the vehicle. FC has relatively low efficiency, in comparison with the battery and capacitors, and generate significant amount of heat, which can damage components of the system, including membranes, which can further reduce the production of electricity. Complex cooling systems have been proposed in [6] to decrease thermal loading of FC. In comparison with battery-based EV, cooling losses in FC-based vehicles are significantly higher and can be compared with the sizes of cooling systems in conventional vehicles with internal combustion engines [4,6]. Large-scale cooling system requires larger FC to be installed, increases overall vehicle's mass and further impacting efficiency of the solution. In most proposed solutions, such system is combined with the cooling system of the drivetrain, however these two systems have different operating temperatures and different heat generation rates, so efficiency of such solutions is not high.

Furthermore, EVs have significant challenges in organisation of ventilation of the cabin due to the limited available resources and complex control strategies over the storage systems. Intensive use of ventilation system leads to the significant decrease in the operating range of EV. Utilisation of the heat, generated by the occupants, specially in the public transport, is a technical challenge [7].

This paper proposes a novel system, which utilises heat, developed in the drivetrain, cabin and FC of high speed train, to heat up liquid hydrogen from the relative storage system. Developed solution allows to reduce cooling system power consumption, organise effective cabin ventilation system and remove pre-heater for the liquid storage, based on the calculated thermal energy balance.

ENERGY BALANCE ANALYSIS

In the project, remotely moving high-speed stings-rail operating vehicle was developed. Such system has lower power consumption during the motion in comparison with the road vehicles [8]. The key savings come from the decreased rolling resistance in the contact couple rail – steel wheels in comparison with the rubber tires with high hysteresis losses. With the growth of speed, the required power in significantly smaller, even for the vehicles with higher capacity of passengers and goods. Remote access to the power was developed to reduce air drag of the contactors, which significantly increase power consumption of the current trains [9].

Developed solution on the operating speed has power consumption of 800 kW due to the high operating speed, dimensions and its capacity. As efficiency of the drivetrain system, including electric motors, power electronics and control system, is around 90% and all losses are generating heat, the heat generation rate was calculated as 80 kW. Based on the health standards and passengers' numbers, ventilation and air conditioning system was designed with the power rating of 5 kW.

Based on the power requirements, the power of the FC was chosen as 900 kW, to meet all requirements of auxiliary loads, maintain high speed and operate with the cooling system. The heat developed in FC, can be calculated using method from [10], and in the efficient range, FC heat generation is 612 kW.

In total, developed system shows the heat generation power of 697 kW of heat, including ventilation, drivetrain cooling and FC temperature maintenance. The flow of the hydrogen was calculated as in (1):

$$G_{H_2} = N \cdot g_{H_2} = 0.0194 \text{ kg/s} \qquad (1)$$

Where G_{H_2} – mass consumption of the hydrogen, N – number of used cells, g_{H_2} – balanced consumption of one cell in the efficiency range.
The heat capacity of the liquid hydrogen can be assessed with equation (2), considering that the hydrogen is stored in Dewar vessels at 0.1 MPa at saturated state with the enthalpy h_1 and then is heated to gas with enthalpy of h_2:

$$Q = h_1 - h_2 = 4.1 \text{ MJ/kg} \qquad (2)$$

Then for the given flow rate in the system, the heat capacity of the system is equal to 79 kW. This energy has constant flow requirements and doesn't change, depending on the environmental conditions.

RESULTS AND DISCUSSION

The heat exchange system was developed, as shown on Figure 2.

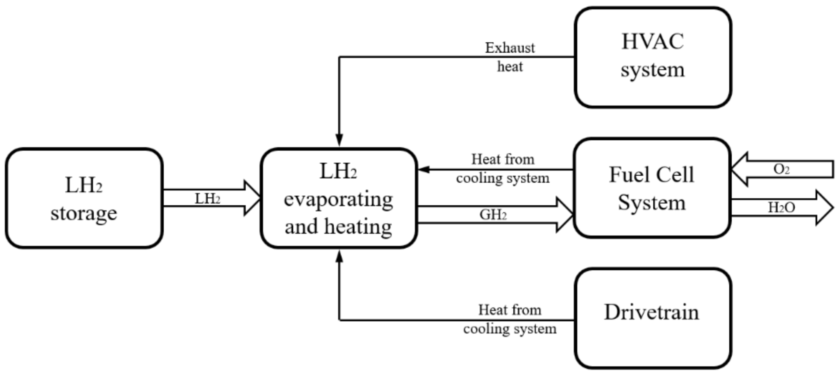

Figure 2. Designed Heat Exhchange System

As it can be seen, the heat generated in various parts of the vehicle, is re-directed to the evaporating chamber of the liquid hydrogen system. The heat dissipation rate in the chamber is 79 kW, however the total required size of the cooling system should have combined capacity of 697 kW. Developed system allows to scale down the required size of the cooling system by 12.9%, with the folloowing gain in the power consumption. Developed system allows to reduce overall complexity of the system, as there is no heating system required for the liquid hydrogen, as the heat is taken from the other systems of the vehicle. This solution can be scaled up or down, depening on the application.

CONCLUSIONS

The paper presents a novel system design, which utilises heat, generated in the various systems of FC EV, including FC, drivetrain and ventilation system, to heat up liquid hydrogen storage system. Developed solution allows to reduce power consumption of the cooling system by 12.9%, which leads to the higher efficiency of the overall system.

REFERENCES

1. Hu, Z., Li, J., Xu, L., Song, Z., Fang, C., Ouyang, M., ... & Kou, G. (2016). Multi-objective energy management optimization and parameter sizing for proton exchange membrane hybrid fuel cell vehicles. *Energy Conversion and Management*, *129*, 108-121.
2. Arlt, M. L., Cardoso, G. F., & Weng, D. (2017, November). Hydrogen storage applications in industrial microgrids. In *2017 IEEE Green Energy and Smart Systems Conference (IGESSC)* (pp. 1-6). IEEE.
3. Gambini, M., Stilo, T., & Vellini, M. (2019). Hydrogen storage systems for fuel cells: Comparison between high and low-temperature metal hydrides. *International Journal of Hydrogen Energy*, *44*(29), 15118-15134.
4. Zohuri, B. (2019). Cryogenics and Liquid Hydrogen Storage. In *Hydrogen Energy* (pp. 121-139). Springer, Cham.
5. Fierro, V., Ramirez-Vidal, P., Sdanghi, G., Schaefer, S., Maranzana, G., & Celzard, A. (2019). Hydrogen adsorption in cryogenic conditions: relationship between the porous texture and the parameters of the Modified Dubinin-Astakhov equation.
6. De las Heras, A., Vivas, F. J., Segura, F., Redondo, M. J., & Andújar, J. M. (2018). Air-cooled fuel cells: Keys to design and build the oxidant/cooling system. *Renewable Energy*, *125*, 1-20.
7. Kavalchuk, I., Arisoy, H., Oo, A. T., & Stojcevski, A. (2014, January). Challenges of electric power management in hybrid and electric vehicles. In *2014 Australasian Universities Power Engineering Conference (AUPEC)* (pp. 1-7). IEEE.
8. Юницкий, А. Э. (2017). *Струнные транспортные системы: на Земле и в космосе*. Belaruskai͡anavuka.
9. Pombo, J., Ambrósio, J., Pereira, M., Rauter, F., Collina, A., & Facchinetti, A. (2009). Influence of the aerodynamic forces on the pantograph–catenary system for high-speed trains. *Vehicle System Dynamics*, *47*(11), 1327-1347.
10. Niknam, T., Bornapour, M., & Gheisari, A. (2013). Combined heat, power and hydrogen production optimal planning of fuel cell power plants in distribution networks. *Energy conversion and management*, *66*, 11-25.