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Recent Advances in Cold-Start and Drive Capability of Fuel Cell Electric Vehicle

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Key Words : Fuel Cell, Fuel Cell Electric Vehicle, Cold-Startup

Abstract : The sub-zero cold is a major environmental consideration for the operational readiness of FCEVs because fuel cells produce water and utilize wet air with varying water content to generate electricity. Typical fuel cells thus have a fatal flaw in freezing conditions at startup. This drawback becomes more serious with the outsourced fuel cell that is entirely water-based for its internal humidification. In this background, the HMC' s self-designed fuel cell was developed as an alternative and was employed in the Tucson-based FCEV in 2006 demonstrating its good cold-startup characteristics. The cold-startup capacity of the vehicle was validated through tests in the cold chamber and on the road, resulting in 50% stack power achieved in 250 seconds at -15℃.

1. Introduction

Recently, there has been a rapidly growing demand for clean and efficient automotive power sources to achieve sustainable mobility. In this background, a fuel cell has drawn wide attention as a promising alternative to a combustion engine. A fuel cell is an electrochemical device that converts chemical energy into electrical energy. Fuel cells can produce electricity directly from electrochemical reactions without multiple energy conversions, including combustion and mechanical motion. Low (near-to-zero) emission as well as high efficiency can therefore be realized in fuel cells, which are envisioned as a power source for a next generation vehicle. [1] Being motivated by such benefits of a fuel cell, many fuel cell alliances among fuel cell manufacturers, automakers, petroleum companies, and government agencies have been formed to research and develop a fuel cell powered vehicle. Since 2000, Hyundai Motor Company (HMC) has been also building fuel cell electric vehicles (FCEVs) and conducting public road tests at home and abroad. [2], [3] Despite of such efforts to expedite the commercialization of FCEVs, there are still many issues to be addressed. For the operational readiness under actual automotive environments, fuel cells must withstand the severe weather conditions as combustion engines do.

In particular, the sub-zero cold is detrimental to the fuel cells to run, especially based on a polymer electrolyte membrane (PEMFC) that is normally employed for automotive applications due to its low operating temperature, fast startup and good dynamic behavior. [4] This paper describes the efforts and results associated with the cold-start and drive capability of the HMC FCEVs, taking into account their performance comparison between outsourced (produced in UTC Power (UTCP)) and in-house fabricated fuel cell stacks from a system perspective.

2. Main Subject

2.1 Progress of FCEV Developments in HMC

HMC developed the Santa Fe- as well as the Tucson-based FCEVs in 2000 and 2004, respectively. For these developments, HMC has teamed up with UTCP to procure a fuel cell stack and its associated components, producing 32 units ('04 model HMC FCEV) offered for the Department of Energy (DOE)'s controlled hydrogen fleet and infrastructure demonstration and validation project. The '06 model HMC FCEV was then introduced, featuring the in-house developed fuel cell stack with which a gross power of 80 kW, almost equivalent to UTCP's, is extractable. Currently, ten units, including two buses, are under the domestic operation for the FCEV learning demonstration led by the Korean government. And now, HMC has newly developed the state-of-the-art '08 model FCEV equipped with a 100 kW-fuel cell stack that was in-house developed, as well.

2.2 Comparison of Fuel Cells

One of the major differences between outsourced and in-house developed fuel cell stacks is a means to humidify the electrolyte membrane in the fuel cell. The electrolyte membrane needs to maintain a high water content to ensure a high proton conductivity, enabling a low resistance to protons to flow through, in turn, the high overall efficiency of the fuel cell. As shown in Fig. 2.1 (a), the UTCP-made fuel cell stack employed in the '04 models was designed to keep their electrolyte membrane wet internally using a de-ionized water (DI Water). The DI Water may function as a coolant in the

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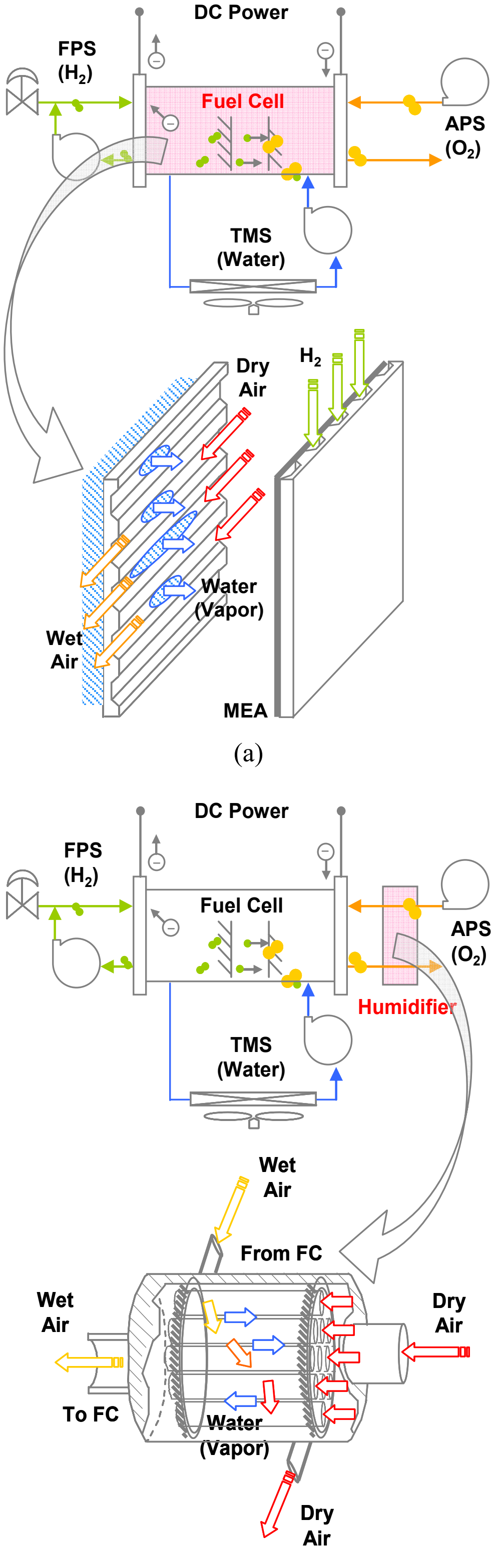

(a)

(b)

Fig. 2.1 Schematic illustration of the fuel cell systems with different air humidification scheme: (a) using a porous flow field between TMS and APS – outsourced fuel cell stack, (b) using an additional humidifier at APS – in-house developed fuel cell stack

thermal management system (TMS), as well. In this structure, due to a porous flow field that can absorb and retain water, the incoming air can be damp so that the electrolyte membrane can be humidified. Such a self-humidification is a simple and easy method but the humidity control is difficult. On the other hands, the HMC-designed fuel cell stack loaded in the ’06 models employed an external humidifier, as shown in Fig. 2.1 (b). In this scheme, the water content in the electrolyte membrane can be controlled by humidifying the incoming reactant gases, the air fed to cathode, in particular. This humidifier uses hot and moist outgoing air to humidify dry incoming air through its membrane. Using such a gas-to-gas membrane humidifier, the water content can be directly transferrable without an extra condenser resulting in a simplified TMS. Furthermore, the gases are allowed to be humidified at temperatures near to the operating temperature of the fuel cell so that the humidifier can work like a heat exchanger, as well. But still, the humidify control is not easy and the given water content may not be sufficient in a full load. Meanwhile, the coolant synthesized especially for this fuel cell is DI Water-based, preventing the presumable electrolyte membrane damage when leaked, but unfrozen at sub-freezing temperatures. The freezing point of this material is controllable with its concentration (down to -37°C).

2.3 Current Status and Problem Statement

For the DOE’s controlled hydrogen fleet and infrastructure demonstration and validation project, a part of fleet vehicles (’04 model HMC FCEV) were scheduled to run at Michigan area from 2004. The FCEVs to be dispatched to this site were thus remodeled for the cold-start and drive at a temperature as low as -10°C. In general, water inside the fuel cell, both retained after the previous operation and produced during the present operation, would freeze during the cold-startup at a sub-zero temperature. Then, the ice inside the fuel cell could thaw if the fuel cell temperature would rise in normal temperatures. Such a freeze/thaw cycle should compromise the fuel cell performance. For this reason, the entirely DI Water-based system including the UTC-made fuel cell needs to be completely drained prior to a soaking at a sub-freezing temperature starts. The drained water is reserved in the rapid thaw accumulator (RTA) enabling partially or fully frozen water to melt during a cold-startup. The melted water is then drawn into the TMS connected to the fuel cell stack by means of a pressure difference induced by a vacuum pump. Besides, all the associated parts and components are expected to withstand such a low temperature; they were not originally created considering a low temperature tolerance, though. To tackle such difficulties and complications, major parts of the systems including the fuel cell stack as well as the balance of plant (BOP) components were reformed and multiple courses during the cold-startup and shutdown were implemented resulting in a successful cold-startup at temperatures as low as -10°C. It normally took about five minutes for the cold-startup plus 90 seconds for the cold-shutdown and consumed approximately 420 Wh of energy in total. Despite of the feasibility shown in many tests, such a time and energy consuming process hardly meet the requirements given in the actual automotive environments. In this background, the HMC-developed fuel cell was recognized as an alternative expecting possible advances in time and energy consumptions as well as a long-term dependability for the cold-startup. In this fuel cell, the water coolant is allowed to remain in the fuel cell stack and also TMS even below 0°C that enables a rapid and efficient cold-startup compared to UTCP's. Such advantages are attainable due to this system's principles that the water coolant needs not contact the electrolyte membrane exploiting the external humidification and the water coolant is formulated to keep unfrozen at sub-zero temperatures. Employing this fuel cell and its associated components, the '06 model HMC FCEV was accomplished and its cold-start and drive capacity was tested under cold weathers.

2.4 Cold-Start and Drive Capability Developed

2.4.1 Fuel Cell Stack Test

Prior to the test using a full-scale vehicle, the concept of a self-start of the fuel cell stack was experimentally validated in a test stand. At -10°C, the fuel cell stack was demonstrated to self-heat to 68°C, its normal operating temperature, in 75 seconds. For such a cold-startup capacity, a heat insulator was applied to maintain the fuel cells stack warm in a cold ambient temperature. Additionally, end plates were improved to reduce the difference in temperatures between cells causing a limit on a stack current. Moreover, the anti-freezing water coolant was prepared, which needs not remove prior to soaking at sub-zero temperatures.

2.4.2 Vehicle Test

Based on the test result from the fuel cell stack, a vehicle-level cold-startup process was established after many trial-and-error iterations. The cold-startup process is made up of three phases in sequence. For the fuel cell preconditioning, the cold-shutdown process is followed by the cold-startup process, which includes the course to minimize the water remained inside the fuel cell by a gas-purge.

○ *Phase 1: BOP (FPS valves) Thaw*

Among valves in the fuel processing system (FPS), the valves located at the outlet of the fuel cell should be frost at the moment of a cold-startup because of outgoing hydrogen that carries a water vapor. These valves thus need to be defrosted by means of either heat or impulse. Impulse is given to the valve for hydrogen-purge in order to reduce the time required whereas heat is provided to the valves for hydrogen-recirculation and trapped water-drain. The pump for the anti-freezing water coolant also works leading to a uniform heat distribution inside the fuel cell stack. However, the fuel cell is not ready to generate electricity so the power required in this stage is totally offered by the high-voltage battery.

○ *Phase 2: CSA (Cell Stack Assembly) Stabilization*

As hydrogen may be fed to the anode in the previous phase, air is then provided to the cathode in this phase, which continues until the stack voltage becomes stable; it normally takes less than 10 seconds. The power consumed for air supply still depends on the high-voltage battery.

○ *Phase 3: CSA (Cell Stack Assembly) Warm-up*

With the stack voltage stabilized, the fuel cell may be loaded so that the electric motor becomes ready to run notwithstanding the limit on the stack current given for motoring. In addition, the discharged high-voltage battery gets recharged through a DC-DC converter and the blower for hydrogen-recirculation begins to drive. Apart from those functions available, the stack current is required to draw to some extent for the fuel cell stack to self-heat, thus to warm-up. This course is ended up with the appreciable rise in the temperature of the air leaving the fuel cell resulting in the ready for full operations with no limit on the stack current.

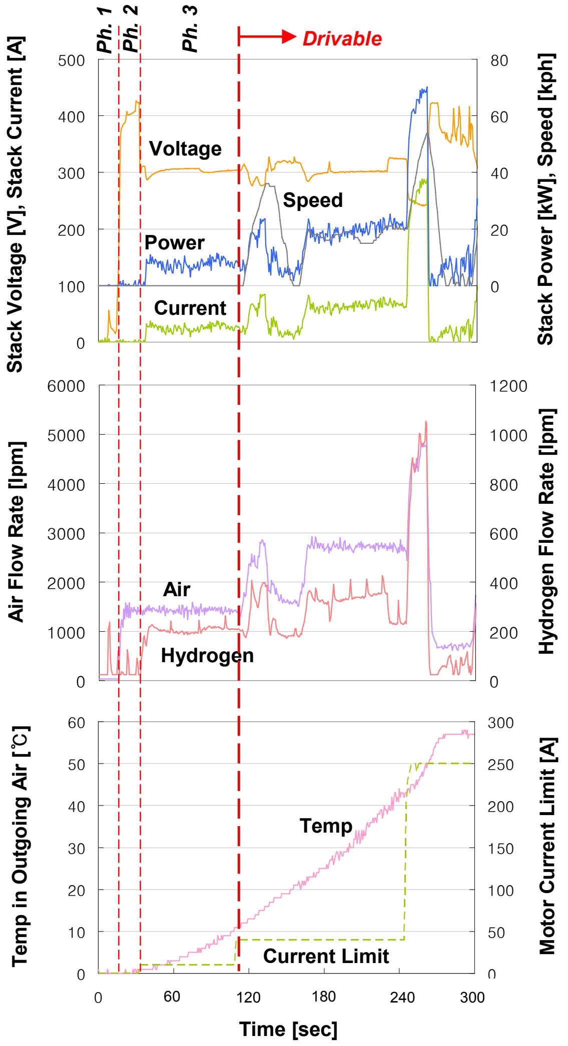

Fig. 2.2 Demonstration of the cold-start and drive capability at -15°C when sitting idle for 24 hours

Being controlled by the cold-startup sequence constructed, the HMC FCEV was successfully demonstrated to cold-startup at -15°C when sitting idle for 24 hours in an environment chamber. While shutdown, the water gathered at the anode water trap was removed to avoid being frozen while cold soaking. As noted earlier, the cold-startup got started with a hydrogen-supply to the fuel cell stack. For the hydrogen-feed the associated valves were thawed, which enables to control the hydrogen flow. As shown in Fig. 2.2, a sharp rise in the hydrogen flow rate at about six seconds was observed, which resulted from the hydrogen-purge valve open in company with the hydrogen-supply valve open, as well. Such a quick response in the hydrogen-purge valve was attributed to impulse applied instead of heat which has taken almost two minutes to have the valve begin to move. With the hydrogen flow obtained, the rise in the air flow rate at about 15 seconds appeared resulting in the increase in the stack voltage. With the stack voltage stabilized, the stack current was observed to flow through a resistor in the heater as well as in the cathode oxygen depletion (COD) apparatus, enabling the self-heat-sustained cold-startup process. During such a fuel cell warm-up, a temperature in the air leaving the fuel cell was gradually increased; once this temperature reached 10°C, the limit on the stack current provided for motoring was changed from 10 A to 40 A. This restriction was fully eliminated with the temperature of 40°C. Following the cold-startup, the cold-drive was carried out under a full load. As noted earlier, for a dependable fuel cell performance in response to a load given, the stack current given for motoring is regulated taking into account the temperature in the outgoing air from the fuel cell. For this reason, the cold drive test resulted in the stack power of 23 kW with the temperature of 15°C, whereas the maximum stack power of 70 kW at the temperature of 47°C. For comparison, the maximum stack power recorded at a normal condition was 78 kW. In Table 1, the obtained results regarding the cold-startup are summarized with the comparison of results from the ’04 model employing the UTCP-made fuel cell stack. As shown in this chart, the ’06 model powered by the HMC-made fuel cell stack demonstrated an approximately 52% shorter time and 85% less energy required for the cold-startup compared to the ’04 model. Much higher time and energy consumed on the ’04 model were largely due to thawing followed by heating the water iced in the RTA. Aside from such results presented, the cold-startup of the ’04 model was extremely tricky due to its vulnerable TMS. The TMS was readily clogged with the ice formed from the water undrained so that the upcoming water could be hindered while startup leading to the undependable result.

Table 1. Cold-startup performance comparison between ’04 model (with UTCP-made fuel cell stack) and ’06 model (with HMC-made fuel cell stack)

Vehicle	’04 model	’06 model
Fuel Cell Stack	Outsourced (UTCP)	In-house developed (HMC)
Min. Temp. [°C]	-10	-15
Time [sec]	244	116
Energy [kJ]	1450	220
Dependability	Weak	Strong

2.4.3 On-site Test

The cold-start and drive capability of the HMC FCEV was on-site tested domestically (near Hangyeryeong area). In this test the vehicle was overnight soaked at this site; while soaking the ambient temperature dropped to -18°C and the wind blew at about 3.5 m/s. In particular, the cold wind, not applied in the environmental chamber, should expedite the stack cooling. In principle, the heat stored in the fuel cell stack is released from the edge to the center. Since the soaking was not long enough to lead to thermal equilibrium through every single cell, the variation in the temperature between cells was expected to be larger than that in the earlier chamber test. Despite of the end cell plates, the temperature in outer cells should be much lower than that in inner cells, which would have a deleterious effect on the cold-startup availability. Such harsh conditions turned out to be compromising to the developed cold-startup capability of the vehicle. The first startup attempt right after overnight soaking failed on account of the particular temperature decrease at the end cell. The end cells were understood not to self-heat enough to maintain electrochemical reactions. Another startup attempts with the water coolant running from the very beginning were subsequently made to set the vehicle in motion. Such startups in series were believed to be favorable to the overall temperature increase in the fuel cell stack. In addition, the water coolant was forced to circulate from the very beginning in order to mitigate the temperature difference among cells. As a result of the on-site validation test, there are a few opportunities suggested for the enhanced cold-startup capacity. As complementary measures for uniform heat distribution throughout cells, in the fuel cell stack, the end cell and its plate need to be reformed for improving the heat insulation, meanwhile, in TMS, the water coolant needs to be heated up rapidly and then circulated.

3. Conclusion

The cold-start and drive capability of the HMC FCEV (’06 model) was successfully developed and demonstrated. Unlike the ‘04 model, the fuel cell stack and its associated components were HMC’s own design. Due to its good cold-startup characteristics, the vehicle was capable of cranking after being subjected to -15°C for 24 hours; it took 116 seconds to be partially loaded and subsequently took another 150 seconds to be fully loaded with the maximum stack power of 70 kW. In addition, the cold-startup using the in-house developed fuel cell system required an approximately 52% shorter time and 85% less energy than that with the outsourced fuel cell system in the ‘04 model.

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