

Development of New H₂ Refueling Method for FCV to Reduce Refueling Time

Kiyoshi HANDA* Steve MATHISON**

ABSTRACT

A new refueling method was developed to shorten the hydrogen refueling time of FCV. The conventional method determined the pressure ramp rate according to the ambient temperature, and the temperature to which the supplied hydrogen is precooled to prevent overheating when refueling did not influence the pressure ramp rate. The new method added real-time control of the pressure ramp rate according to the precooled hydrogen temperature. Consideration was also given to compatibility, so the only changes to the hydrogen refueling station side were the addition of a temperature sensor and software changes, and no changes to the control and hardware on the vehicle side are needed. Under the conditions above, vehicle tests were performed with the cooperation of General Motors and Mercedes-Benz, with the result that the new refueling method enabled shortening of the refueling time in the summer by 30% or more compared to the conventional method and without lowering the precooled hydrogen temperature. This enables refueling in less than four minutes in most cases year-round in the Los Angeles district, United States. In addition, a State of Charge equivalent to that of the conventional method was also secured.

1. Introduction

The fuel used as the power source for automobiles began with coal and has gone through changes to petroleum, natural gas and hydrogen. This is the history of carbon reduction, and at the same time is also the history toward smaller molecules. Having reached the smallest molecule, hydrogen, automobiles have now achieved carbon-free driving.

On the other hand, a higher storage pressure is required compared to conventional fuel. As a result of seeking a driving range equivalent to that of a gasoline vehicle, the vessel pressure of fuel cell vehicles (FCV) has reached 70 MPa. SAE has taken a leading role in establishing standards to help achieve the safe refueling of this high-pressure hydrogen. An issue unique to hydrogen refueling is heat generation inside the vessel of the vehicle. The refueling system basically consists of four heat transfer systems connected in series (Fig. 1). The hydrogen is cooled (precooled) to approximately -40°C (I) to prevent it from overheating inside the vessel of the vehicle. The temperature of the cooled hydrogen is increased by the heat mass of the breakaway, hose, nozzle and other station parts (II) and the heat mass of the vehicle tube (III). When the hydrogen enters the vessel, it is compressed, which

generates heat (IV). That final temperature needs to be 85°C or less in accordance with requirements such as the ANSI standard⁽¹⁾.

When the ambient temperature (T_{amb}) is high, the refueling time is lengthened to promote the diffusion of heat to the vessel body. The pressure ramp rates at which overheating does not occur are obtained from hundreds of simulation times, and these results are compiled into a data table and stored in the hydrogen refueling station control unit. Refueling is performed while referencing this table, so this is called the look-up table (L/T) refueling method.

The actual control first measures the ambient temperature, and then reads the pressure ramp rate from the table and controls the flow control valve to maintain a fixed pressure ramp rate during refueling. Assuming the SAE standard conditions (ambient temperature T_{amb} 20°C, initial pressure P_0 10 MPa), refueling completes in approximately 3 1/2 minutes (the black circle in Fig. 2).

High ambient temperatures are an issue for the L/T refueling method. The maximum temperatures were analyzed for the Los Angeles (LA) district, U.S. which is one of the main markets, and the results showed that the temperature with a cumulative frequency of 98% was 35°C. The refueling time at 35°C requires up to five minutes or more, which is thought to be an issue for customer

* Automobile R&D Center

** HONDA R&D AMERICAS, INC.

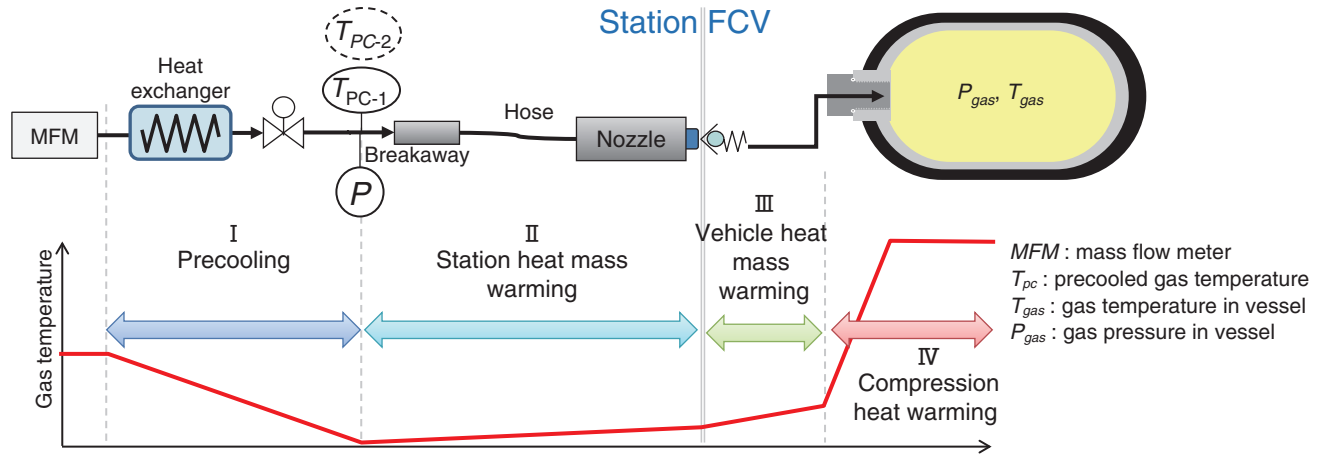


Fig. 1 Overall refueling system

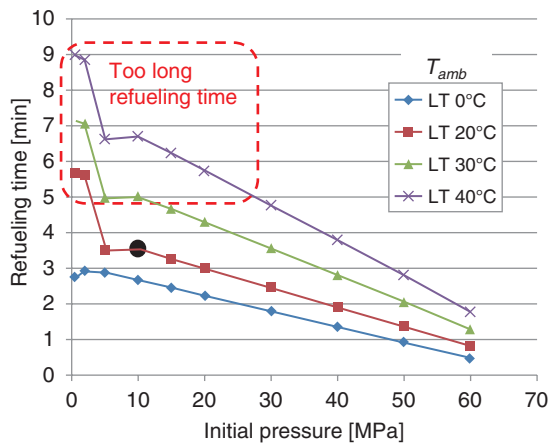


Fig. 2 Effect of ambient temperature

satisfaction. Therefore, Honda has conducted original research on hydrogen refueling technology^{(2), (3)}. The newly developed refueling method was named the MC-Formula refueling method. Here, M comes from the Mass inside the vessel, C comes from the heat Capacity of the vessel, and Formula comes from the fact that the pressure ramp rate is calculated in real time using a numerical formula. This paper introduces this MC-Formula refueling method.

2. Development Goals

The new refueling method was developed with the following goals.

- (1) Refueling is completed in less than 4 minutes even during the summer in the LA district.
- (2) The approach toward safety is carried over unchanged from the L/T refueling method.
- (3) The FCV system is not changed.
- (4) The hydrogen refueling station hardware is changed as little as possible. Changes to the software are limited to version upgrades with downward compatibility.

The L/T refueling method constantly maintains a fixed pressure ramp rate. This pressure ramp rate is set for the case when the precooled hydrogen temperature is -33°C , which is the upper limit of the specified tolerance, but the actual temperature is lower than this tolerance upper limit (Fig. 3). This means that the refueling time is the same even when the actual temperature is lower than -33°C .

However, when the precooled hydrogen temperature is lower, it should be possible to perform refueling faster in accordance with the lower temperature inside the vessel (Fig. 4).

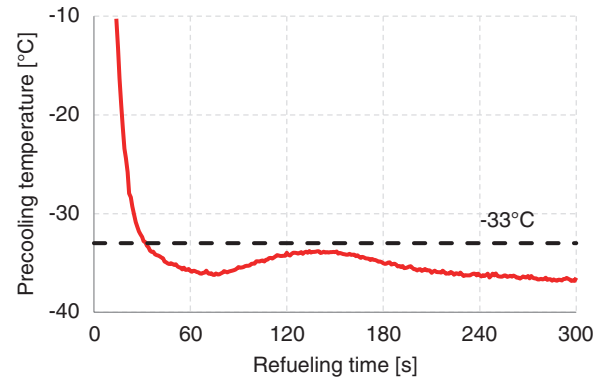


Fig. 3 Example of precooling temperature

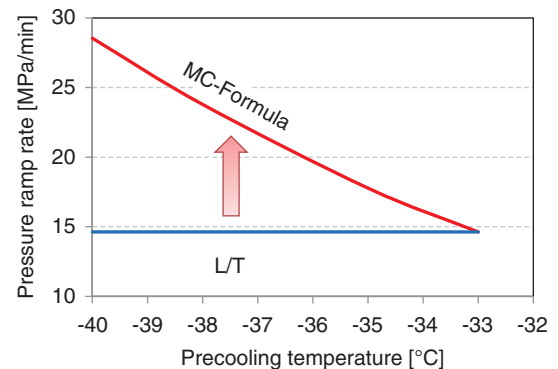


Fig. 4 Effect of precooling temperature

It is thought that if the pressure ramp rate could be determined in real time in accordance with the actual precooled hydrogen temperature, refueling could be performed more quickly even at the same precooled hydrogen temperature.

3. System Configuration

A method that calculates the pressure ramp rate in real time from the measured precooled hydrogen temperature was created for the control software.

3.1. Mass Average Processing of the Precooled Hydrogen Temperature

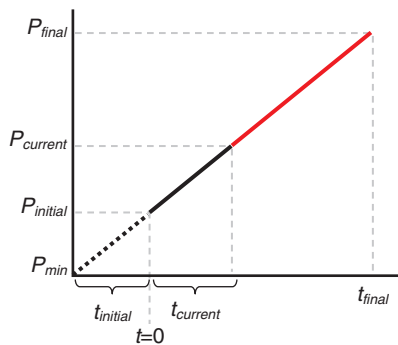
The pressure ramp rate is determined based on the precooled hydrogen temperature sensor value (T_{PC}) in Fig. 1. Equation (1) was used to perform mass average processing on the precooled hydrogen temperature using the mass flow rate sensor value m . Here, i is the control time step.

$$MATC(i) = \frac{\sum_1^i [(m(i) - m(i-1)) \times 0.5(T_{PC(i)} + T_{PC(i-1)})]}{\sum_1^i (m(i) - m(i-1))} \quad (1)$$

3.2. Introduction of a Refueling Time Parameter

The refueling time t_{final} was made into a parameter in order to add precooled hydrogen temperature feedback control (Fig. 5).

t_{final} is the refueling time after refueling starts from the specified initial pressure (P_{min} 0.5 or 5 MPa) until refueling ends at the specified end pressure (83.5 MPa). For example, when refueling is started from the initial pressure $P_{initial}$ of the vehicle's vessel, this is viewed as starting from partway through refueling that started from P_{min} . When the initial pressure $P_{initial}$ of the vehicle is



t_{final} : time required to refuel from P_{min} to P_{final}

$t_{current}$: time measured since refueling began

$t_{initial}$: imaginal time before refueling began

P_{final} : maximum allowed dispenser pressure

$P_{current}$: current dispenser pressure

$P_{initial}$: initial pressure when refueling began

P_{min} : minimum allowed starting pressure

Fig. 5 Pressure ramp rate control methodology

higher than P_{min} , the amount of heat generated inside the vessel decreases. Therefore, only the P_{min} case, which has the greatest amount of heat generation, needs to be considered.

Two different P_{min} were prepared to shorten the practical refueling time. The case when $P_{initial}$ is 5 MPa or less is the rare case immediately before running out of fuel. In this case, the compression ratio and the amount of heat generation increase, so the refueling time becomes quite long. If this case is used as the premise for control, the refueling time would become longer even for other, more typical cases in order to support a few rare cases. For this reason, the case with 5 MPa or less is handled separately in the control.

3.3. Calculation of the Pressure Ramp Rate in Accordance with the Precooled Hydrogen Temperature

The MC-Formula refueling method performs refueling by varying the pressure ramp rate that was a fixed value according to the ambient temperature with the L/T refueling method.

In Fig. 5, actual refueling starts from $P_{initial}$, so this point is $t = 0$ in actual time. Here, the time $t_{initial}$ from P_{min} to $P_{initial}$ is a hypothetical refueling time that does not actually exist. $t_{initial}$ is obtained by Eq. (2) from the proportional distribution of the pressure.

$$t_{initial} = \left(\frac{P_{initial} - P_{min}}{P_{final} - P_{min}} \right) \times t_{final} \quad (2)$$

t_{final} is the value including the hypothetical time $t_{initial}$. This is calculated for each ambient temperature and each precooled hydrogen temperature. The condition is that the hydrogen temperature inside the vessel reaches the upper limit of 85°C at t_{final} . Overheating occurs when filling is performed faster than this t_{final} , so t_{final} is the shortest refueling time. This t_{final} calculation simulates the complex heat transfer phenomena inside the tube and vessel, and six precooled hydrogen temperature patterns $\times$ 15 ambient temperature patterns = 90 patterns are calculated beforehand via simulations. In this development, the boundary conditions, vessel and other parameters in the simulations used the same values as those of the conventional L/T refueling method.

The relationship between the precooled hydrogen temperature and t_{final} at any given ambient temperature was approximated using a cubic equation to provide continuity.

$$t_{initial}(T_{amb}) = a(T_{amb}) \times MATC^3 + b(T_{amb}) \times MATC^2 + c(T_{amb}) \times MATC + d(T_{amb}) \quad (3)$$

Fifteen different combinations of the coefficients a , b , c and d can be set for each ambient temperature. These combinations expressed in table format are called maps in the MC-Formula refueling method. These maps have two

initial pressure patterns $\times$ four vessel capacity patterns for a total of eight maps that are stored in the hydrogen refueling station control unit.

Concretely, the map is selected according to the vessel capacity and the initial pressure, and the coefficients a , b , c and d are determined by the ambient temperature. Linear interpolation is performed at the intermediate temperatures. t_{final} can then be calculated by substituting the measured mass average precooled hydrogen temperature $MATC$ into the equation.

Next, the pressure Ramp Rate (RR) is calculated from t_{final} .

According to Fig. 5, at the actual current time $t_{current}$, the required pressure difference until the end of refueling is $P_{final} - P_{current}$. The time required for this is expressed by Eq. (4) using Eq. (2).

$$\begin{aligned} t_{final} - t_{initial} - t_{current} &= t_{final} - \left(\frac{P_{initial} - P_{min}}{P_{final} - P_{min}} \right) \times t_{final} - t_{current} \\ &= \left(\frac{P_{final} - P_{initial}}{P_{final} - P_{min}} \right) \times t_{final} - t_{current} \end{aligned} \quad (4)$$

Therefore, at $t_{current}$, the pressure ramp rate until the end of refueling is the ratio of the pressure difference to the time, and can be expressed by Eq. (5).

$$RR = \frac{P_{final} - P_{current}}{t_{final} \left(\frac{P_{final} - P_{initial}}{P_{final} - P_{min}} \right) - t_{current}} \quad (5)$$

When RR has been determined, the target pressure to be achieved at the next control step (i) is given by Eq. (6).

$$P_{(i+1)} = P_{(i)} + RR_{(i)} \times (t_{(i+1)} - t_{(i)}) \quad (6)$$

The control method that performs flow control for the hydrogen refueling station to reach the target pressure is exactly the same as that used by the L/T refueling method. This enabled a feedback of the actual precooled hydrogen temperature to the refueling time without overheating.

3.4. End Pressure Setting

The gasoline full state can be detected by the height of the fuel surface. The hydrogen pressure changes according to the temperature, so it cannot be used as a full state index. For this reason, the full state is defined by the density. SAE J2601⁽⁴⁾ defines a hydrogen density of 40.2 kg/m³ at a temperature of 15°C and pressure of 70 MPa as a State Of Charge (SOC) of 100%.

However, the hydrogen density cannot be measured directly, so it needs to be calculated from the pressure and temperature. Therefore, SAE J2799⁽⁵⁾ established a communication refueling system (IR communication system) that sends the information of the temperature inside the vessel of the vehicle to the station via IR communication. This enabled real-time calculation of the hydrogen density for accurate full vessel judgment.

The method of ending refueling is basically the same as that of the L/T refueling method. The temperature inside the vessel is received from the vehicle via IR communication, the hydrogen density is calculated, and refueling is stopped.

Figure 6 shows an overall image of this control.

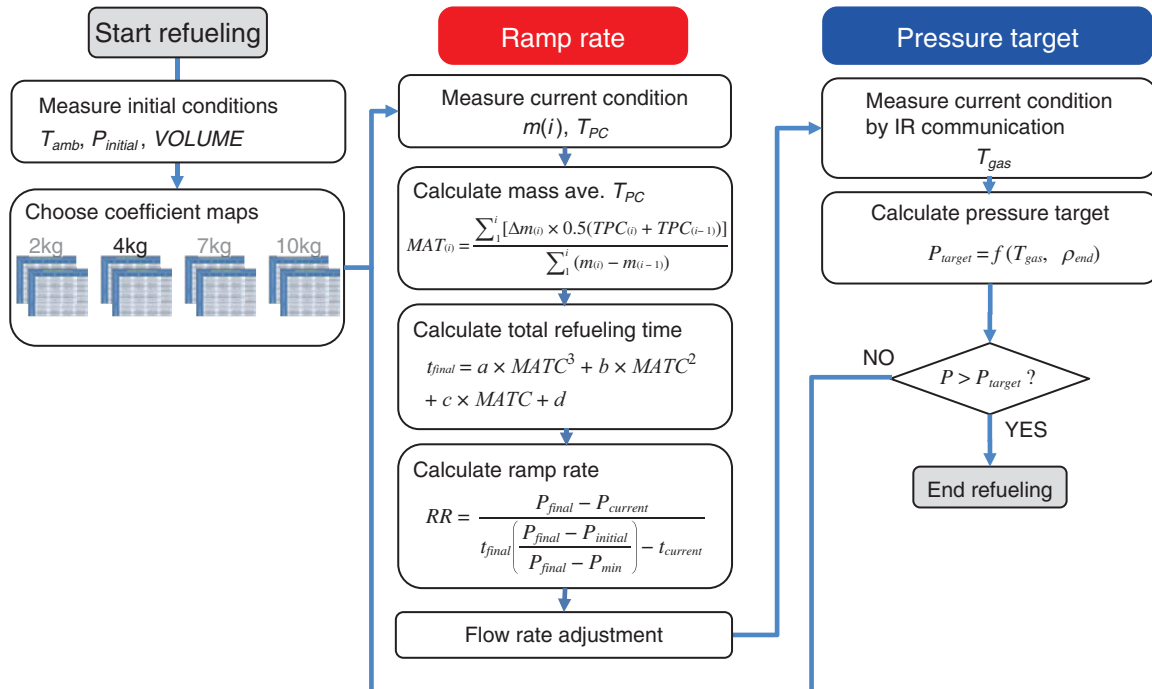


Fig. 6 MC-Formula refueling control structure

3.5. Hardware Configuration

3.5.1. Addition of a precooled hydrogen temperature sensor

The only change from the L/T refueling method is the addition of the precooled hydrogen temperature sensor T_{PC-2} shown in Fig. 1. T_{PC-1} and T_{PC-2} measure the temperature in the same location, and compare the measured values with each other. When an issue occurs in either sensor, the values diverge, enabling failure detection. Note that there is no change in the maximum hydrogen flow rate, so there is no need for changes to the hydrogen tube or other parts.

3.5.2. Control unit

The MC-Formula refueling method uses a larger amount of calculations than the L/T refueling method. That said, the MC-Formula refueling method requires only one cycle of 1360 floating decimal point calculations every few seconds, which can be supported by a programmable logic controller (PLC), which is a type of compact computer commonly used to control typical facilities. Actual operation showed that the MC-Formula refueling method software operates without issues on a previous-generation PLC that requires 125 μ sec per floating decimal point operation.

4. Proving Tests

The MC-Formula refueling method was introduced to a commercial hydrogen refueling station made by Airproducts Inc., which is the most common type in the U.S., and refueling tests were performed under various conditions using actual FCV and a test vessel.

4.1. Hydrogen Refueling Station

The tests were performed using a hydrogen refueling station at the Honda R&D Los Angeles Center in the City of Torrance, CA, U.S.A. This hydrogen refueling station is able to use both the L/T and MC-Formula refueling methods (Fig. 7).



Fig. 7 Hydrogen refueling station at which MC-Formula was applied

4.2. Test Vessels and Vehicles

Three different types of vessel system were used, two of which were actual FCVs. Cooperation was obtained from General Motors (GM) and Mercedes-Benz for the tests.

The GM Equinox FCV has three vessels with a total capacity of 114 liters (Fig. 8).

The Mercedes-Benz B-Class F-CELL FCV has three vessels with a total capacity of 95 liters (Fig. 9).

The vessel system used to measure the temperature used an aluminum liner vessel with an internal capacity of 105 liters (Fig. 10). Two thermocouples were inserted to



Fig. 8 Photo of General Motors Equinox FCV



Fig. 9 Photo of Mercedes-Benz F-CELL FCV



Fig. 10 Photo of single vessel test rig

measure the hydrogen temperature inside the vessel. The heat capacity of the tube parts (tubes, valves, other) was set to the maximum heat capacity noted in SAE J2601. The pressure drop in the tube was also adjusted to the maximum SAE J2601 value using a needle valve.

4.3. Test Results

The results showed that the refueling time could be shortened while observing the upper limit of the hydrogen temperature inside the vessel, and that an SOC equivalent to that of the conventional L/T refueling method could be obtained.

4.3.1. Refueling time

The tests were performed on days with a high ambient temperature, and test data was obtained at temperatures up to around 35°C. Data at higher temperatures was not obtained, so some temperatures that differ from the actual temperatures were tested by manual input. Vehicle tests were performed at the actual temperatures without manual input. Figure 11 shows the refueling time results. The variance in the data is due to factors such as different initial pressures and the need for leak checks during refueling as prescribed by laws and regulations unique to the U.S.

When the ambient temperature is low, there is negligible concern for overheating, and the pressure ramp rate is limited by the rate upper limit value, so there is no difference between the two methods. The difference between the methods widens as the ambient temperature increases. In contrast to the L/T refueling method that assumes a precooled hydrogen temperature that is the upper limit value of the temperature tolerance, the MC-Formula refueling method uses the actual hydrogen temperature, so the refueling time was approximately 30% shorter. This enabled refueling in less than four minutes in most cases in the LA district.

4.3.2. Hydrogen temperature inside the vessel

Figure 12 shows the hydrogen temperatures inside the

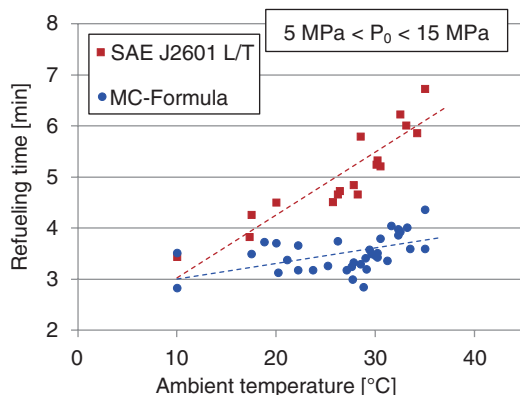


Fig. 11 Refueling time on ambient temperature

vessels of the GM Equinox FCV at the end of refueling. These results show that although the hydrogen temperature rose by an average of approximately 8°C due to the increased pressure ramp rate, the temperature was still 70°C or less, which is sufficiently below the upper limit value of 85°C.

The reason for this is thought to be that the three-vessel system has a large vessel wall surface area relative to the hydrogen quantity, so the hydrogen is cooled by the heat mass of the vessel body and the hydrogen temperature does not rise easily.

4.3.3. SOC

Figure 13 shows the SOC during communication refueling.

This station has an end target of an SOC between 98% and 100%. Both refueling methods calculate the density and perform end of refueling control using the temperature obtained by communication refueling. The control method is the same, so no difference was apparent in the actual SOC.

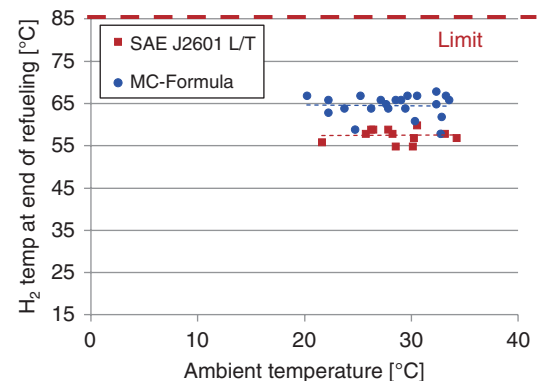


Fig. 12 Ending H₂ temperature in vessel

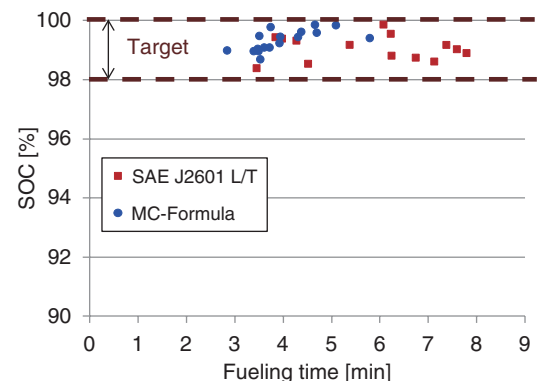


Fig. 13 Ending SOC of communication refueling on test vessel

5. Conclusion

The MC-Formula refueling method was developed to shorten the hydrogen refueling time of FCV.

- (1) Real-time control of the pressure ramp rate in accordance with the precooled hydrogen temperature was added. This made it possible to shorten the refueling time by 30% or more in the summer without lowering the precooled hydrogen temperature, which enables refueling in less than four minutes in most cases year round in the LA district.
- (2) The boundary conditions, vessel and other parameters in the simulation of t_{final} that determines the pressure ramp rate used the same values as those of the L/T refueling method, and the approach toward safety was also carried over. The refueling end method is also the same, which helped to achieve an SOC equal to that of the conventional L/T refueling method.
- (3) No changes were made to either the hardware or the software on the vehicle side.
- (4) The only change to the hydrogen refueling station hardware was the addition of a temperature sensor. The amount of calculations performed by the hydrogen refueling station software increased, but the software was able to operate on the previous-generation PLC. Therefore, the developed system can also be installed in existing stations.

6. Afterword

The MC-Formula refueling method is currently under deliberation as a proposed revision to the SAE J2601 standard (as of July 2015).

References

- (1) ANSI HGV 2-2014: Compressed hydrogen gas vehicle fuel containers (2014)
- (2) Harty, R., Mathison, S.: Improving Hydrogen Tank Refueling Performance Through The Use Of An Advanced Fueling Algorithm - The MC Method, Proceedings of the National Hydrogen Association Conference (2010)
- (3) Mathison, S., Handa, K., Mcguir, T., Brown, T., Goldstein, T., Johnston, M.: Field Validation of the MC Default Fill Hydrogen Fueling Protocol, SAE Technical Paper, 2015-01-1177 (2015)
- (4) SAE J2601: Fueling Protocols for Light Duty Gaseous Hydrogen Surface Vehicles (2014)
- (5) SAE J2799: Hydrogen Surface Vehicle to Station Communications Hardware and Software (2014)

■ Author ■



Kiyoshi HANDA



Steve MATHISON