# Verification of a novel hydrogen refueling method for HDVs

## - Significant reduction for refueling time and hydrogen pressure storage volume -

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**ABSTRACT**: Current hydrogen stations for passenger FCV are using a constant dispenser hydrogen pressure ramp rate method. When a hydrogen flow rate increases for heavy duty vehicle, a large pressure loss occur and it slows down refueling. To compensate for this tube pressure loss without any feedback from the vehicle, a novel method (cTPR method) which has the hydrogen constant pressure ramp rate in the vehicle tank was developed. A refueling testing with cTPR method at full commercial scale confirmed that a refueling time can be shortened. cTPR makes it possible to use the pressure storage capacity for hydrogen more efficiently and to reduce the number or volume of pressure storage tanks. cTPR can also help to reduce the cost of building and operating refueling stations.

**KEY WORDS**: Fuel cell vehicle, Hydrogen station, Refueling, HDV, Pressure loss

## 1. INTRODUCTION

Society of Automotive Engineers (SAE) has formulated the J2601-1 standard[(1)] for safe refueling of high-pressure hydrogen, which refuels for fuel cell passenger vehicles (light-duty vehicles: LDVs), and Look-up table method (L/T method) was published in 2014. According to requirements such as the ANSI standard[(2)], the temperature in the vehicle tank during refueling needs to be 85°C or less, so hydrogen is cooled (precooled) to around -40°C for refueling. HONDA had independently researched hydrogen refueling technology[(3)-(5)] and developed an MC Formula refueling method that can variably control the pressure ramp rate in real time even if the precooled hydrogen temperature fluctuates. This method was adopted in SAE J2601-1(2016) [(1)] and shortened the refueling time by up to around -30%.

HONDA, ENEOS, and TOKICO System Solutions conducted research[(6)] which funded by New Energy and Industrial Technology Development Organization (NEDO) to relax the precooling temperature. MC Multi Map (MC-MM) method was developed that has multiple refueling control maps according to the thermal capacity of the hydrogen refueling tube system and also the initial pressure of FCV. MC-MM can reflects the cold state of the tube due to refueling of the previous vehicle. This enabled relaxing the precooling temperature. MC-MM was adopted as JPEC S0003(2023) [(7)]. A thermal mass measuring method which was developed for MC-MM was adopted as new JPEC S0012(2023) [(7)].

These LDV refueling methods ramp the pressure of the hydrogen station dispenser at a constant rate, so they are referred to here as the constant dispenser pressure ramp rate method (Fig. 1). In addition, this is a feed-forward method that basically does not use the FCV sensor information and performs flow rate control only using the information of sensors on the station side. This method has the following merits.

1. Simple pressure control on the station
2. Simple and inexpensive system on the FCV
3. Even if refueling is temporarily interrupted for some reason and then resumed, the pressure ramp rate (PRR) is the same as first PRR and stability is high.

NEDO constructed the "Fukushima Hydrogen Refueling Technology Research Center" (FTC)[(8)] in Namie Town in Fukushima Prefecture, Japan. The tank internal volume of HDVs are an order of magnitude larger than that of LDVs. As the flow rate is large, the tube pressure loss increases even if the diameter of the hydrogen refueling tube of HRS (Hydrogen refueling station) is increased. As a result, there are the following issues with the constant dispenser pressure ramp rate method. Especially at low pressure, the pressure loss is large and the flow rate is restricted. The pressure in the tank ramps, but due to tube pressure loss, the ending SOC is not easily reached at the end of refueling, and the refueling time lengthens. A higher dispenser supply pressure is needed to increase the flow rate at low pressure, but this is contrary to the concept of the constant dispenser pressure ramp rate method. Lue et al. proposed Two-stage APRRs method.[9]. And SAE J2601-5 TIR[10] also proposed PRR TAPER method. These change PRR during the refueling then it needs two more parameter which are when and how to change it.

In the United States, National Renewable Energy Laboratory (NREL) has constructed an experimental hydrogen station for HDVs[11]. In the EU, a research project called PRHYDE[12] was conducted for two years from 2020. In place of the constant dispenser pressure ramp rate method, a method (MC Formula Throttle) has been proposed in which the signal from a temperature sensor in the tank is fed back to the station and used in flow rate control. Another easily conceivable option is the method of feeding back the pressure sensor signal of the FCV. These methods can handle the high-level pressure loss of HDVs with relatively simple control. In addition, a method incorporates real-time simulation[13] has also been proposed. However, realistically there are the following issues. The FCV sensor needs the same level of accuracy as the station and periodical inspection. In particular, it is necessary to vent all the hydrogen in the tank when inspecting the temperature sensor in the tank, which incurs extremely high maintenance cost. As all FCVs are involved in the pressure ramp rate control of the station, the number of related parts increases by orders of magnitude and the failure rate in the market also increases substantially. FCV owners are often individuals, and there is also the possibility of illegal modifications, etc.

Therefore, the feedback method increases the maintenance cost burden on users and also poses issues for securing refueling safety. In other words, a refueling method is demanded that addresses the pressure loss issue specific to HDVs while using a feed-forward method as before.

However, as hydrogen stations are built by various manufacturers, the specifications are not the same. Likewise, FCVs also come in a variety of models, each with a different tank size and tubes. Even given the same model, the pressure loss state differs due to the filter clogging state, etc. In other words, a characteristic of commercial hydrogen stations is that the pressure loss state differs with each refueling.

It is well known in fluid engineering that even with the same tube system, the pressure loss varies greatly due to changes in the pressure, flow rate, and temperature. Advanced theorizing is needed to deal with such dynamically changing pressure loss.

HONDA invented a new control method to realize a feed-forward refueling method. And authors group has been developing a new refueling protocol technology with this new method since 2023 June. [14] This paper introduces this new control method.

## 2. SYSTEM CONSTRUCTION

### 2.1. cTPR method

In the conventional station, the dispenser pressure increases constantly (Fig.1), the tank pressure increases slowly due to small pressure difference between the dispenser and the tank. In the later half, the pressure loss decreases and the flow rate is obtained. The time vs. the tank pressure curve is unpredictable, so the end of refueling is delayed.

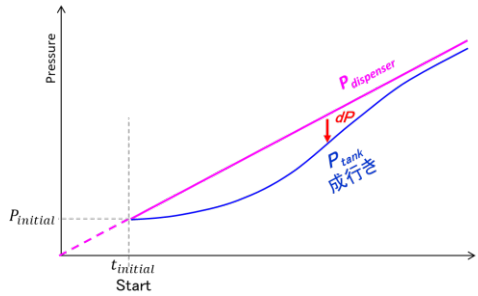


Fig. 1 Constant dispenser pressure ramp rate method

In cTPR method, the station supplies a higher pressure (Fig.2) that includes the tube pressure loss in order to keep the constant pressure ramp at the tank. The pressure loss is predicted and refueling is performed using a simple control formula (Eq.2, Eq.3) using the tank volume: V, pressure ramp rate: $\psi$, and the tube pressure loss coefficient: k0 which is measured during refueling [15]. The required accuracy and reliability of FCVs are the same as those of conventional LDVs, so there is no increase in vehicle costs or maintenance costs.

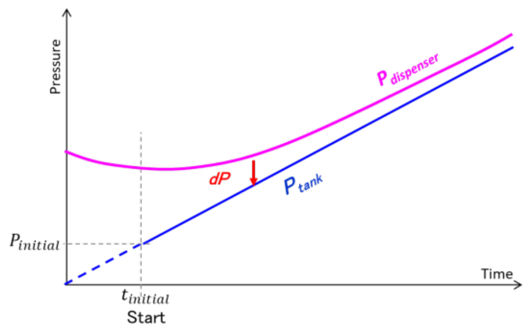


Fig. 2 Constant Tank Pressure Ramp rate method

$$k_0 = \frac{\Delta P \times \rho_{tube}}{\dot{m}^2} \qquad \text{Eq.1}$$

$$\dot{m} = \frac{dm}{dt} = \frac{\psi VRT}{(RT+\psi tb)^2} \qquad \text{Eq.2}$$

$$P_{dispenser} = \frac{k_0\dot{m}^2 b}{2} + \sqrt{\left(\psi t - \frac{k_0\dot{m}^2 b}{2}\right)^2 + 2k_0\dot{m}^2(RT_{tube} + b\psi t)}$$

Eq.3

## 3. VERIFICATION TEST

### 3.1. Hydrogen station

### 3.1 Test site

The test was conducted at FTC [8]. There are three pressure storage banks in total. Each storage (2700L) consists of nine storage tanks which has 300L volume each. Type-2 tanks (49kg-$H_2$ or 80kg-$H_2$) simulating an HDV FCV were refueled. Since there is no communication device between the dispenser and tanks, the end of refueling was determined using the target pressure table for non-communicating refueling in the dispenser constant ramp rate method. In the cTPR method, the end of refueling was determined using the temperature of the simulated tank (measured via wire). Because it is a Type-2 tank, the gas temperature in the tank is lower than Type-4 and the end pressure is also lower. Since the ending conditions of both methods are different, the refueling end time was estimated by extrapolating the tank pressure of the dispenser constant ramp rate method. The tube pressure loss coefficient between the storage and dispenser was defined as $k_1$, and $k_0$ between the dispenser and FCV. A schematic diagram is shown in Figure 3.

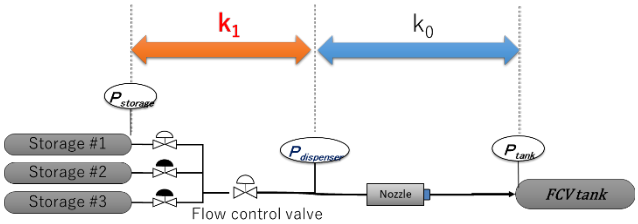


Fig.3 Pressure loss coefficient in Station and FCV

### 3.2 Twin nozzle dispenser

There are two medium flow nozzles in one dispenser (Fig. 4), which are operated in parallel simultaneously. To reduce pressure losses, modifications were made to the dispenser and hydrogen supply tubes between the pressure storages and dispenser. A refueling test was conducted before and after the modifications.

### 3.2.1 Normal flow dispenser (before modification)

Two normal flow nozzles were connected in parallel (Fig. 4), and the maximum flow rate was 120 g/s.

Fig. 4 Hydrogen refueling dispenser and nozzles at FTC

### 3.2.2 Medium flow dispenser (after modification)

To comply with HDV, the nozzle were changed to medium flow specifications, and the maximum flow rate became 90g/s×2=180g/s. Additionally, the diameter of the internal tubes of dispenser was enlarged. And the flow rate control valve was replaced to a larger flow rate one. Furthermore, the diameter of the supplying tubes from pressure storages to the dispenser was also enlarged. The coefficients were k1=3.44×$10^{10}$ $m^{-4}$, resulting in a reduction of -52%, and k0=2.81×$10^{10}$ $m^{-4}$, resulting in a reduction of -34%.(Fig.5)

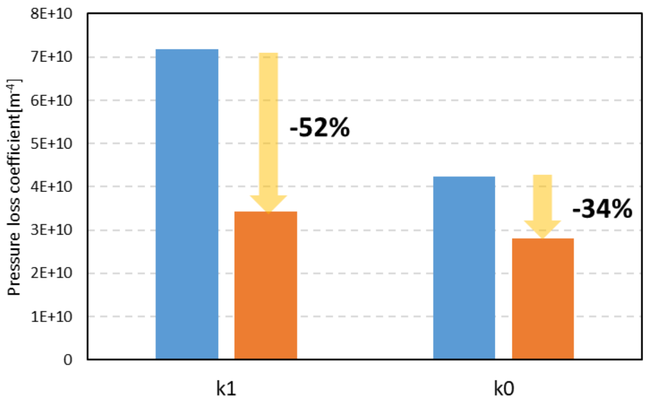


Fig.5 Pressure loss coefficient reduction by modifications

### 3.3 Test results

3.3.1 Normal Flow Twin Nozzle

Figure 6 shows the test results of refueling 80 kg-$H_2$ tank with APRR = 5MPa/min. The upper shows the pressure and the lower shows the mass flow rate. For comparison, the dispenser constant pressure ramp rate (conventional) method is shown in black, and the results of cTPR method are shown in red.

The dispenser pressure with the conventional method was able to maintain the original pressure ramp rate (upper black solid line) until about 680 seconds. After that, the pressure in the pressure storage was insufficient, the ramp rate decreased, and direct refueling from the compressor was the main source to ramp. Finally, refueling was completed in 1011 seconds.

The tank pressure with cTPR method (upper red dotted line) shortened the refueling time by 194 seconds while maintaining a nearly constant pressure ramp rate and refueling was completed in 817 seconds.

The mass flow rate of the conventional method (lower black solid line) reached its peak after the middle of refueling. Since it was not possible to maintain a large flow rate in the high-pressure range, the second pressure storage was switched to the third pressure storage in a short time. However, the third pressure storage was also unable to maintain the flow rate, and as mentioned above, the refueling time was significantly extended. On the other hand, cTPR method (lower red solid line) had the largest flow rate at the beginning and then gradually decreased. This made it easy to maintain the flow rate, and the pressure storage switching was generally at equal intervals.

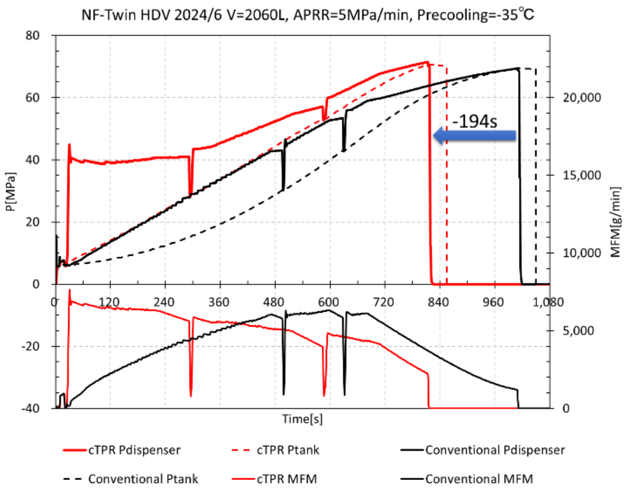


Fig. 6 Test result of 80kg-H2 tank with twin normal flow nozzles

Fig.7 shows the test results of refueling 49 kg-$H_2$ tank with APRR=8.3MPa/min. The conventional method (lower black dot line) used a third pressure storage, but the pressure ramp (upper black solid line) began to drop at about 400 second and refueling was completed in 530 seconds. The tank pressure with cTPR method (upper red dot line) maintained the ramp rate until the end of refueling, shortening the refueling time by 81 seconds and completing refueling in 449 seconds. In this case, refueling (lower red dot line) was completed with the second pressure storage, and the third pressure storage was not necessary.

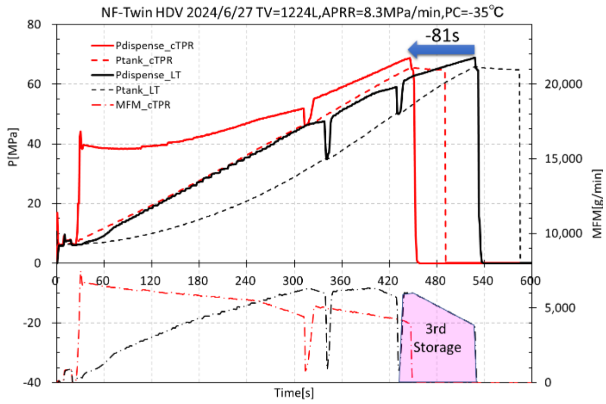


Fig.7 Test result of 49kg-H2 tank with twin normal flow nozzles

3.3.2 Medium Flow Twin Nozzle

Figure 8 shows the test results when 80 kg-$H_2$ tank was refueled with APRR=5MPa/min. Unlike the results in Figure 6, both methods were able to maintain the pressure ramp rate until the end of refueling. This is because the amount of hydrogen released from the pressure storage increased due to an overall reduction in pressure loss in the hydrogen tubes. When compared at the same tank ending pressure, cTPR method was able to reduce the refueling time by approximately 50 seconds. At the start of refueling, the dispenser pressure for cTPR method dropped from 40MPa in Figure 6 to 30MPa due to the reduction in k0.

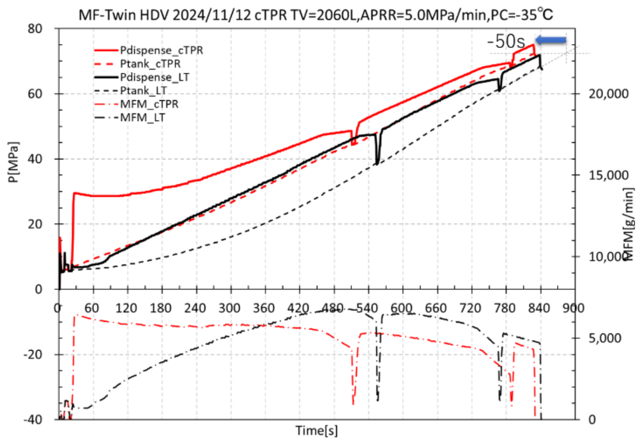


Fig. 8 Test result of 80 kg-$H_2$ tank with twin medium flow nozzles

Figure 9 shows the test results of refueling 49 kg-$H_2$ tank with APRR=8.3MPa/min. With both refueling methods, refueling ended with the second pressure storage stage, and a third pressure storage was not required. When comparing the same tank ending pressure, the cTPR method was able to reduce the refueling time by 35 seconds. The dispenser pressure of the cTPR method at the start of refueling dropped from 40MPa in Figure 7 to 34MPa.

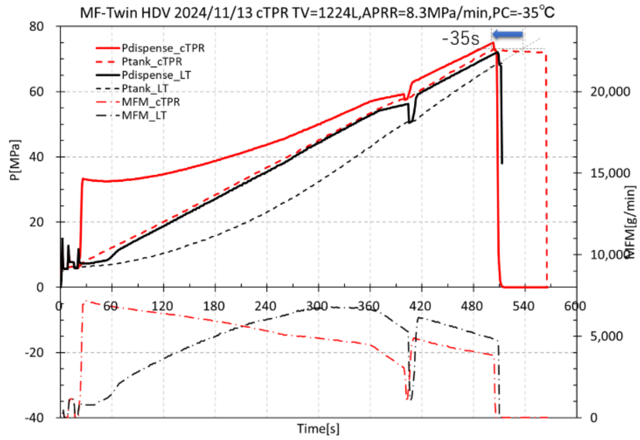


Fig.9 Test result of 49kg-$H_2$ tank with twin medium flow nozzles

3.3.3 Effects of $k_1$

Figure 10 shows the storage pressures, the dispenser pressure and flow rate in the conventional method with 80kg-$H_2$ tank before the modification. Because $k_1$ was larger, the pressure loss between the storage and the dispenser was a maximum of 20 MPa or more at 490s. Around 625s, the flow rate could not be maintained, so the second storage was switched to the third storage in a short time.

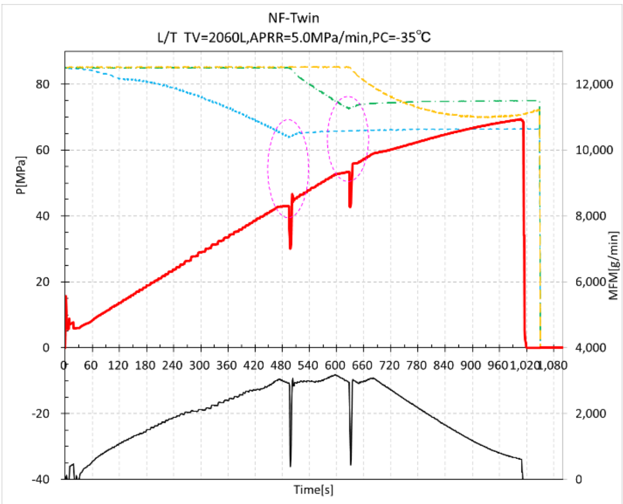


Fig.10 The pressure of each storage before the modification

Figure 11 shows the results for the medium flow twin dispenser. By reducing the tube pressure loss, the first and second storages could be used down to a lower storage pressure. It was unexpectedly discovered that $k_1$ has an effect on the overall refueling, especially on the effective utilization of the storages.

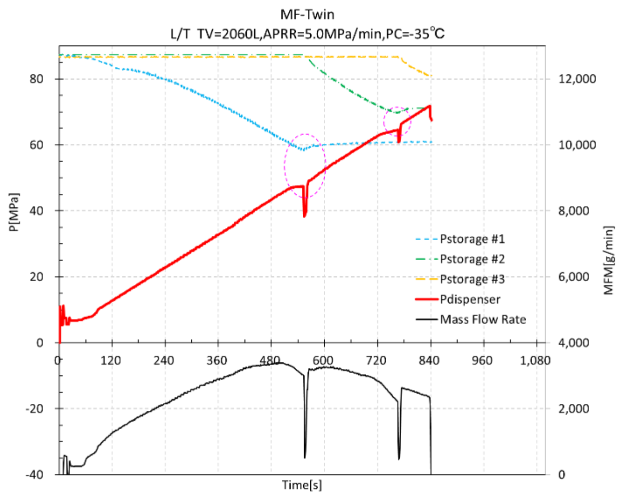


Fig.11 The pressure of each storage after modification

## 4. CONCLUSIONS

1. cTPR refueling test was conducted on a full-size HDV tank using the twin nozzle method.

2. The tank was pressurized at a constant tank pressure ramp rate by feed-forward control without using the vehicle pressure signal.

3. cTPR method has a shorter refueling time by minutes.

4. cTPR method has a large mass flow rate at low tank pressure, so the pressure storage is more efficient in use, and by reducing the number of pressure storages or their volume, it can also contribute to reducing station costs.

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