Development of Real-time Pressure Loss Compensation Method for Hydrogen Refueling Station to Increase Refueling Amounts

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ABSTRACT: A new real-time pressure loss compensation method was developed for hydrogen refueling stations to increase fuel cell vehicle driving ranges. Pressure loss coefficient measurement every refueling enabled to distinguish the conditions of each vehicle and the station. A time-lag pressure loss measuring method was utilized to accurately get the pressure loss without the vehicle’s data. The vehicle tank pressure was accurately estimated only from the station’s measurement data. As a result, the vehicle’s SOC was enhanced by an average of 4.6%.

KEY WORDS: EV and HV systems, Energy replenishment/hydrogen filling/infrastructure, Cooling/heat and temperature management, MC Formula fill, Pressure loss compensation (A3)

1. Introduction

Standards such as SAE J2601(1) and JPEC S0003(2) have been issued to help achieve the safe refueling of high-pressure hydrogen fuel for fuel cell vehicles (FCV) (as of November 2017).

One new point for hydrogen refueling, when compared to conventional liquid fuels, is detection of a full state. A gasoline full state can be detected by fuel surface height. However, the pressure of gaseous fuels changes according to temperature, so the pressure is insufficient as a full state index. For this reason, a full state is defined by density. SAE J2601 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, hydrogen density cannot be measured directly, so it needs to be calculated from the pressure and temperature. Therefore, SAE J2799(3) established a communication refueling system (IR communication system) that sends the temperature information from inside the vehicle tank to the hydrogen refueling station via infrared (IR) communication. This enables real-time calculation of the hydrogen density for full state judgment.

Honda has conducted original research on hydrogen refueling technology(4)-(7), and the MC Formula refueling method, which enables real-time flexible control of the pressure ramp rate even when the precooled hydrogen temperature fluctuates, was adopted in the 2016 edition of SAE J2601(1). This enabled shortening the refueling time by up to approximately 30%. However, the full state detection method was the same as before, so there was no change in the end-of-fill SOC(6).

There are fewer hydrogen refueling stations than gasoline stations, so even a slightly higher SOC is desirable for FCV. SAE J2601(1) stipulates that pressure measurement during refueling is to be performed by the hydrogen refueling station side. However, pressure loss occurs inside the tube during hydrogen refueling, so the vehicle tank pressure becomes less than the hydrogen refueling station’s pressure measurement value (Fig. 1). This means that when the full state is judged by the pressure sensor of the hydrogen refueling station, the tank is not actually full.

As a result, it is a well-known fact in the hydrogen refueling industry that a loss on the level of several percent occurs in the SOC.

Various methods can be considered to compensate this loss, for example, by subtracting a fixed pressure loss value from the hydrogen refueling station pressure measurement value to estimate the vehicle tank pressure. However, excessive compensation may lead to over-filling. Pressure loss is influenced by factors such as the flow rate (0 to 60 g/s), pressure (0.5 to 87.5 MPa), temperature (-40°C to 50°C), the tube’s inner diameter, tube length, and the presence of narrow flow paths, so it differs greatly according to a variety of refueling conditions. For this reason the subtraction value tends to be modest in consideration of varying circumstances. It makes insufficient compensation.

Therefore, a method that can account for the various conditions and accurately estimate pressure loss is needed in order to enhance the SOC during refueling and increase the driving range.

The authors devised a new method for estimating the pressure loss coefficient during refueling in order to enhance the end-of-fill...
2. Development Goals

A real-time pressure loss compensation method was developed with the following goals.

1. Measurement of the pressure loss coefficient for each vehicle during refueling
2. Compensation of the end-of-fill pressure in accordance with the measured pressure loss coefficient
3. Realization simply by changing the software, without altering the hydrogen refueling station hardware

3. System Configuration

The specifics of the real-time pressure loss compensation method are described below.

3.1. Introduction of Pressure Loss Coefficient Measurement Every Refueling

SAE J2601\(^1\) stipulates that the pressure loss upper limit must be 15 MPa or less on the hydrogen refueling station side and 20 MPa or less on the vehicle side. However, this is the upper limit specification, and is different from the actual pressure loss.

The tube on the hydrogen refueling station side does not change every refueling, but the pressure loss is thought to change gradually over time due to the influence of differing factors, such as the dust filter inserted into the tube system. In contrast, the vehicle differs every refueling, so the pressure loss also differs. Therefore, to accurately measure the pressure loss by only one side, it is necessary to perform measurement every refueling. Even if the tube system is constant, the pressure loss is influenced by the flow, pressure, and temperature. These values change dynamically during refueling, so to estimate the pressure loss in an arbitrary state, it is necessary to arrange the process in a format that assigns a unique pressure loss coefficient to the tube system.

3.2. Introduction of Time-lag Pressure Loss Coefficient Measurement

The pressure loss is the difference between the hydrogen refueling station pressure and the vehicle tank pressure, so it is necessary to know the vehicle tank pressure. This paper refers to the method that measures the pressure loss using pressure sensors on both the hydrogen refueling station and vehicle sides as a double sensor method.

FCVs measure the vehicle tank pressure using a pressure sensor on the vehicle side, and send this information to the hydrogen refueling station by infrared (IR) communication system. The double sensor method is established between the pressure sensors on the hydrogen refueling station side and the vehicle side. However, these two sensors are not normally calibrated for accuracy, so errors occur. Furthermore, when refueling without communication, there is no signal from the vehicle, so the double sensor method cannot be used. Therefore, the double sensor method is not suited for refueling in the market.

In principle, accuracy calibration issues will not occur if the vehicle tank pressure can also be measured using the pressure sensor of the hydrogen refueling station. The U.S. NFPA\(^4\) standard stipulates that the flow should be temporarily stopped and leak checks performed during refueling. At that time gas is not flowing, so the pressure loss is zero and the hydrogen refueling station and vehicle tank pressures are the same. This process can be utilized to measure the vehicle tank pressure with the hydrogen refueling station side sensor. Pressure loss occurs immediately before starting the leak check, and the change in the pressure before and after starting the leak check can be regarded as the pressure loss (Fig. 2). This paper refers to this method as the single sensor time-lag method. This method has the issue that it can be used only at the timing when starting or ending the leak check, so the number of measurement points is limited. However, the pressure loss coefficient is thought to be constant during refueling, so this is thought to be sufficient for application to pressure loss compensation in the market.

On the other hand, it is necessary to perform other tasks, such as closing the flow control valve, when starting the leak check, and these take some time. In addition, mass flow meters are known to generally have a slower measurement response speed compared to pressure sensors. Accordingly, preliminary tests showed that correct measurement values cannot be obtained immediately after the leak check process starts. For this reason, the pressure is measured (i in Fig. 2), the leak check is then started immediately, and after waiting for 3 s until the pressure stabilizes (i + 3 s in Fig. 2), measurement is performed again in a state without pressure loss.

The method of using the measured values to calculate the pressure loss coefficient is described below. The pressure loss of the flow path is generally given by Eq. (1) using the non-dimensional loss coefficient \(\zeta\), gas density \(\rho\), and gas flow velocity \(v\).

\[
dP_{\text{loss}} = \zeta \rho \frac{v^2}{2}
\]  
(1)

The hydrogen refueling station does not measure flow velocity \(v\), but it always measures the mass flow rate \(m\) using a mass flow meter for charge calculation and refueling control. Therefore, Eq. (1) is modified to the mass flow rate format. The relationship between the flow velocity and the mass flow rate is expressed by Eq. (2) using the flow path sectional area and the gas density.

\[
v = \frac{m}{\text{Area} \times \rho}
\]  
(2)
Substituting Eq. (2) into Eq. (1) obtains Eq. (3).

\[
dP_{loss} = \left( \frac{\zeta}{2 \text{Area}^2} \right) \left( \frac{\dot{m}^2}{\rho} \right)
\] (3)

Here, \( k_0 \) in Eq. (4) below is a [m\(^2\)] unit value unique to the flow path, and is called the pressure loss coefficient in this paper. This value includes both the hydrogen refueling station and vehicle tube systems.

\[
k_0 = \left( \frac{\zeta}{2 \text{Area}^2} \right)
\] (4)

By using Eq. (4), Eq. (3) changes as follows.

\[
dP_{loss} = k_0 \left( \frac{\dot{m}^2}{\rho} \right)
\] (5)

Eq. (5) transforms into Eq. (6) as follows, enabling to obtain \( k_0 \) by measurements.

\[
k_0 = \frac{dP_{loss} \cdot \rho}{\dot{m}^2}
\] (6)

The tube pressure \( dP_{loss} \) is measured during the leak check. However, the gas density inside the tube is a function of the gas pressure and temperature, and is expressed by Eq. (7).

\[
\rho \left( \frac{P_{\text{dispense}, i} + P_{\text{dispense}, i+3\text{sec}}}{2} \right) \frac{\dot{m}^2}{T_{\text{dispenser}}} (7)
\]

The gas pressure is obtained by calculating the average pressure inside the tube using the single sensor time-lag method shown in Fig. 2.

The gas temperature is then measured using the precooling temperature sensor. The density should use the average temperature inside the tube, but there is no temperature sensor at the tube outlet, that is to say, at the vehicle side tank inlet, causing calculation to be a challenge. Fortunately, the influence of temperature on density is small, at approximately -0.28 %/°C (50 MPa, -40°C to 0°C), so the inlet temperature can be substituted for the average temperature without major error.

This means that \( k_0 \) can be measured by a single leak check process.

3.3. Real-time Estimation of Pressure Loss

The method of using the pressure loss coefficient to estimate pressure loss is described below.

The pressure loss \( dP_{loss, estimated} \) can be estimated in real time by applying the mass flow rate measured in real time, the gas density calculated from the tube pressure and the gas temperature, and then the measured \( k_0 \) to Eq. (5). This is not the leak check timing, so the density used in Eq. (5) cannot be used in Eq. (7). Therefore, the dispenser pressure was used instead, as shown in Eq. (8). In this case the density is higher than that calculated using the average pressure inside the tube, so the estimated pressure loss is smaller than the true value. As a result, refueling ends early and the SOC drops slightly.

\[
dP_{loss, estimated} = k_0 \left( \frac{\dot{m}^2}{\rho(P_{\text{dispenser}(\text{current})}^2 - T_{\text{gas}(\text{current})}^2)} \right)
\] (8)

The estimated vehicle tank pressure \( P_{\text{tank, estimated}} \) is obtained from the estimated pressure loss and the dispenser pressure as shown in Eq. (9).

\[
P_{\text{tank, estimated}} = P_{\text{dispenser}} - dP_{loss, estimated} \] (9)

The estimated SOC value \( \text{SOC}_{\text{estimated}} \) is obtained from the estimated vehicle tank pressure and the temperature inside the vehicle tank \( T_{\text{IR}} \) obtained from the communication refueling system as shown in Eq. (10). This enables full state judgment with real-time pressure loss compensation.

\[
\text{SOC}_{\text{estimated}} = \rho \left( P_{\text{tank, estimated}}, T_{\text{IR}} \right) / 40.2 \text{kg/m}^3
\] (10)

3.4. Flow Chart

Figure 3 shows the overall control schema. When starting the leak check after the start of refueling, the process jumps to the leak check subroutine (Fig. 4) and gets the pressure loss coefficient. The pressure loss coefficient is used to estimate the vehicle tank pressure as necessary, and check whether the SOC has reached the end condition. If the SOC has not yet reached the end condition, refueling continues.

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**Fig. 3 Overall structure of new control**

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3.5. Hydrogen Refueling Station Hardware Configuration

3.5.1. Hardware changes

The system described above enables compensation of the pressure loss in real time without any changes to the hardware.

4. Proving Tests

Refueling tests were performed using a commercial hydrogen refueling station made by Air Products Inc., which is the most common type in the U.S.

4.1. Hydrogen Refueling Station

The tests were performed at the Honda R&D Los Angeles Center in the City of Torrance, CA, U.S. This hydrogen refueling station is able to use both the Lookup Table (L/T) refueling method and the MC Formula refueling method (Fig. 5). The loss coefficient \( k_0 \) was calculated by the Program Logic Controller (PLC) that controls this hydrogen refueling station.

4.2. Test Vehicle Tank

The Type 4 tank system prepared for the automobile protocol test was used. Two vehicle tanks with internal capacities of 90 L and 30 L were mounted.

4.3. Test Results

4.3.1. Pressure, precooling temperature, and mass flow rate measurement results

Figure 6 shows the transitions in pressure, the precooling temperature and mass flow rate during refueling. A maximum pressure loss of 13.8 MPa occurred between the hydrogen refueling station and the vehicle tank. The leak check process was performed three times during refueling, and the mass flow rate was zero during these periods. Of course the pressure loss was also zero, so the hydrogen refueling station and vehicle pressures matched during these periods. The precooling temperature reached a fairly steady state after approximately 50 s.

Figure 7 shows the test results. The horizontal axis shows the refueling time, and the vertical axis shows the pressure loss coefficient. The gas temperature, pressure, and flow change during refueling, but the pressure loss coefficient exhibited a fairly constant value. However, the mass flow rate was zero during the leak check, so the pressure loss coefficient was also zero at that time. In addition, the flow changes greatly when jumping to and returning from the leak check subroutine, as well as when switching the pressure accumulator, so some unstable values were seen. This is thought to occur due to factors such as the sensor response delay. Except for circumstances where there are concerns over a response delay, this shows that the developed pressure loss estimation method is effective even in a tube system consisting of an actual hydrogen refueling station and a vehicle.
The asterisks in Fig. 7 indicate the pressure loss measurement results obtained using the single sensor time-lag method.

4.3.3. Pressure loss estimation accuracy results

Figure 8 shows the results of estimating the pressure loss using the data in section 4.3.1 above, and the pressure loss coefficient measured using the time-lag method in section 4.3.2 above. The horizontal axis shows the measured pressure loss, and the vertical axis shows the pressure loss estimated from k0 using Eq. (8). The error tended to be larger during the first half of refueling, but then decreased and became stable toward the end of refueling.

4.3.4. SOC enhancement results

Tests were performed with a vehicle tank initial pressure between 5 and 40 MPa. The pressure accumulator of this hydrogen refueling station had slightly insufficient capacity, so there were cases where the completely full state was not reached depending on the initial pressure. Therefore, this study did not perform end-of-fill control using Eq. (10), and instead virtual SOC evaluation was performed by analyzing the data after the test. The temperature inside the vehicle tank TIR was virtually offset by \( dT_{IR} (\text{from } -40^\circ \text{C} \text{ to } -20^\circ \text{C}) \). This resulted in an apparent increase in the SOC of approximately 4 to 8%. The time when the SOC determined using this virtual data exceeded 98% was used as the end-of-fill time. (Note: \( dT_{IR} \) is a kind of tentative technique to analyze this insufficient test data in SOC. This is not a permanent method for data analysis or station’s control.) When the dispenser pressure is used as is, the end-of-fill judgment is as shown in Eq. (11). This end time is labeled \( t_{end\text{-dispenser}} \).

\[
SOC = \frac{\rho (P_{\text{tank}} T_{IR} + dT_{IR})}{40.2 \text{kg/m}^3} \geq 98% \quad (11)
\]

However, Eq. (11) includes pressure loss, so it is not the true value. The vehicle tank SOC is obtained by Eq. (12) using the tank pressure at \( t_{end\text{-dispenser}} \).

\[
SOC_{\text{dispenser}} = \frac{\rho (P_{\text{tank}} T_{IR} + dT_{IR})}{40.2 \text{kg/m}^3} \quad (12)
\]

Likewise, when using the estimated vehicle tank pressure value in Eq. (9), the end-of-fill judgment is as shown in Eq. (13). This end time is labeled \( t_{end\text{-estimated}} \).

\[
SOC = \frac{\rho (P_{\text{tank\text{-estimated}}} T_{IR} + dT_{IR})}{40.2 \text{kg/m}^3} \geq 98% \quad (13)
\]

The vehicle tank SOC at this time is obtained by Eq. (14) using the tank pressure at \( t_{end\text{-estimated}} \).

\[
SOC_{\text{estimated}} = \frac{\rho (P_{\text{tank}} T_{IR} + dT_{IR})}{40.2 \text{kg/m}^3} \quad (14)
\]

The two end-of-fill times differ as shown in Eq. (15), \( t_{end\text{-dispenser}} < t_{end\text{-estimated}} \), and results in a longer refueling time, which increases the SOC.

\[
I_{end\text{-dispenser}} < I_{end\text{-estimated}} \quad (15)
\]

Figure 9 shows the SOC comparison results. The horizontal axis shows the initial pressure and the vertical axis shows the SOC. The developed pressure loss estimation method enabled to increase the SOC by an average of 4.6%.

5. Conclusion

A real-time pressure loss compensation method was developed to enhance the hydrogen SOC of fuel cell vehicles.

1. A method that measures the pressure loss coefficient every refueling was devised which can address the issues of pressure loss differences between vehicles and the influence of changes in the hydrogen refueling station condition over time.
2. Use of the time-lag pressure loss measuring method enabled accurate measurement of pressure loss using only the pressure sensor of the hydrogen refueling station.
3. The vehicle tank pressure could be estimated in real time using the measured pressure loss coefficient.
4. The SOC could be increased by 4.6% by changing the pressure used for the end-of-fill judgment from the dispenser pressure to the estimated vehicle tank pressure.

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