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Development of Fuel Economy Measurement Method for Fuel Cell Vehicles

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Abstract

Fuel consumption measurement of fuel cell vehicle is considerably different from internal combustion engine vehicle fuel consumption measurement. Therefore a practical method of fuel economy measurement has been developed for fuel cell vehicles. The weight method is selected as the primary measurement method for our study because weight method simply can get the best result. Our paper will address the equipment modifications, measurement methods and test results used to accommodate chassis-dynamometer fuel economy testing of a hydrogen-fueled, light-duty vehicle

Key words :Hydrogen, Fuel cell, Energy consumption

1. Introduction

Recently, due to the global environmental issues such as environmental problems and global warming, and fossil energy depletion problems, efforts to solve these problems are made by all over the world very actively. And also in the vehicle industry, not only it is needed to improve the efficiency of existing internal-combustion engine, powertrain and materials, but also the advent of vehicles using alternative energy is strongly needed. Under these requirements, the interests on the developments of Fuel Cell Vehicles(FCVs) which does not have harmful emissions and is pollution-free vehicles is growing. And including Korea, Japan, America, European countries and also many other countries are hurry in the developments of FCVs. According to this, the Fuel Economy Measurement of FCVs could be one of the important criterions to evaluate its economic efficiency and commercialization. However, in the case of FCVs, 'Carbon Balance Method' which is a method of Fuel Economy Measurement for previous internal-combustion engine, cannot be applied to FCVs. So a solution has to be set up to solve it.

Currently, before the mass production of FCVs, regulations and testing methods of FCVs has been preparing in Korea. And accordingly, this research was conducted by KATRI(Korea Automobile Testing & Research Institute) to secure data base for establishment of fuel economy measurement method.

2. Testing Method and Equipments

2.1 Measurement Method

There are ISO 23828 “Fuel cell road Vehicles - Energy consumption measurement - Vehicles fuelled with compressed hydrogen"[1] and J2572 "Recommended Practice for Measuring Fuel Consumption and Range of Fuel Cell and Hybrid Fuel Cell Vehicles Fuelled by Compressed Gaseous Hydrogen"[2] of SAE(Society of Automotive Engineers) in US which is the major standard for the fuel economy measurement method of FCVs, and several research papers on this have been presented. This research also composed of measurement methods and equipment based on above standard and study results, and fuel economy measurement for real FCV was conducted. An overview of measurement methods applied in this research is as follows.

2.1.1 Gravimetric Method

Gravimetric method is measuring the weight of the testing vehicle’s fuel tank before and the after the fuel economy measurement test, and calculating the amount of hydrogen consumption. In this research, this method was decided as a primary measurement method, because as in the matter of measurement principle, it is easy to measure and calculate the amount of hydrogen consumption, and it can get exact results. In addition, it can directly correct equipment in the testing field using standard mass. Eq. (1) is the numerical formula of measurement principle and Figure 1 is the schematic of gravimetric method

$$W = g_1 - g_2 \qquad (1)$$

Here, W : Hydrogen consumption(g), g_i : The weight of hydrogen tank at the start(or completion) of the test

But there is a defect that gravimetric method is impossible to measure the amount of hydrogen consumption in real time. And a special weigh balance which can measure heavy weigh and also can do precise measurements at the same time is required, since it should measure relatively small amount of hydrogen consumption than the weight of heavy hydrogen fuel tank in the real measurement. Moreover, according to the way which connects the testing vehicle with the external hydrogen fuel tank, sometimes elementary quantity of hydrogen could exist in the connecting line, and the amount should be reflected on the result of measurement.

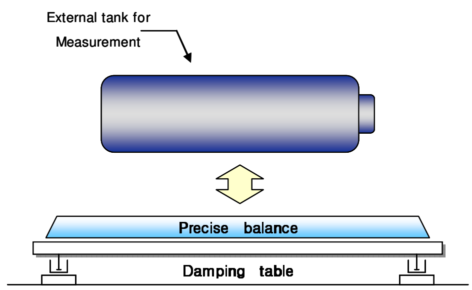


Figure 1. Schematic of gravimetric method

In this research, equipment was composed by a high precision scale which can measure relatively small amount of hydrogen changes that is in heavy hydrogen fuel tank correctly. And its specification is shown as Table 1.

Table 1. Specification of balance for weight method

Maximum load	64.1 kg
Readability	10 mg
Repeatability of nominal load	25mg(60kg)
Repeatability of low load	10mg(5kg)

2.1.2 Flow Method

Flow method is a direct measurement method which measures flowing hydrogen in the fuel pipe using a proper flow sensor. Its measurement principles can be simply expressed as Eq (2).

Following Figure 2 is the schematic of flow method.

$$W = (\sum b) \times \frac{m}{22.414} \quad (2)$$

Here, W : Hydrogen consumption(g), $\sum b$: Integrated flow of hydrogen at standard conditions(273K, 101.3 kPa), m : Molecular weight of hydrogen (2.01588 g/mol)

The benefit of the flow method is that it is possible to measure hydrogen consumption in real-time. However, proper flow sensors are needed accordingly the amount of supplied hydrogen flow and pressure, to get more exact measurement results. So, the selection of the hydrogen flow sensor is important.

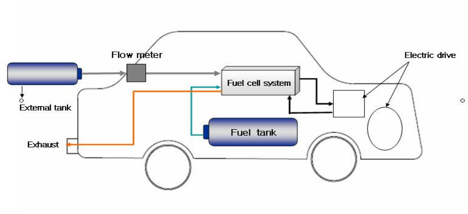


Figure 2. Schematic of flow method

Hydrogen flow sensor as specified in Table 2 was used in this research, in order to cover the defect of gravimetric method, which it cannot measure hydrogen consumption in real-time. And amount of fuel was measured without any change of pressure by lowering hydrogen fuel supplying pressure and the supplying pressure which is supplied into fuel cell system to 1MPa.

Table 2. Specification of hydrogen flow sensor for flow method

Sensor Type	Thermal MFC
Flow Range	0 slm ~ 500 slm
Accuracy	± 1 % of F.S.
Response Time	Under 0.5 sec
Linearity	0.2 % of F.S.
Repeatability	0.2% of Reading

2.1.3 Pressure Method

Pressure method calculates the hydrogen consumption with Eq (3), after measuring the pressure and the temperature of the hydrogen fuel tank which its interior capacity is known.

$$\begin{aligned} W &= m \times (n_1 - n_2) \\ &= m \times \frac{V}{R} \times \left(\frac{P_1}{z_1 \times T_1} - \frac{P_2}{z_2 \times T_2}\right) \end{aligned} \quad (3)$$

Here, W : Hydrogen consumption(g), m : Molecular weight of hydrogen (2.01588 g/mol), V : Volume(ℓ) of hydrogen tank, R : Gas constant (0.008314472 MPaℓ/molK), n, P, T : Mol number, Pressure(MPa), Temperature(K), z : Compression factor at P, T

In the case of pressure method, when the precision capacity of hydrogen tank is known, through measuring pressure and temperature preciously and using proper compression factor for the related with temperature[3][4], the correct result can be obtained. However, a considerable error could be generated by the measuring locations in the hydrogen tank and the time for soaking hydrogen tank which is needed to measure the temperature after the test. So, in this case of measurement, more attention and time is needed[1][5], and there is disadvantage that time is required for soaking.

On the other hand, there are also benefits. As shown in the Figure 3, in the case of using pressure and temperature sensors which is equipped on the hydrogen tank in basic, it can measure hydrogen consumption without high cost measurement equipment. And unlike gravimetric method and flow method, it does not need additional modification on the testing vehicle to connect measurement equipment, so it can measure hydrogen consumption by driving on the real road, not in the laboratory.

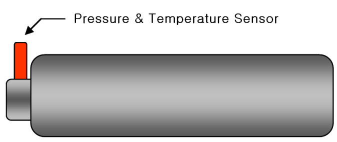


Figure 3. Location of pressure & temperature sensor of hydrogen fuel tank

Compression factors used for pressure method were calculated by Eq. (4) and related constants were presented in Table 3.[6]

$$Z(p,T) = \frac{p}{\rho RT} = 1 + \sum_{i=1}^{9} a_i \left(\frac{100\ \mathrm{K}}{T}\right)^{b_i} \left(\frac{p}{1\ \mathrm{MPa}}\right)^{c_i} \quad (4)$$

Table 3. Constants associated with the density equation for normal hydorgen.

i	a_i	b_i	c_i
1	0.05888460	1.325	1.0
2	-0.06136111	1.87	1.0
3	-0.002650473	2.5	2.0
4	0.002731125	2.8	2.0
5	0.001802374	2.938	2.42
6	-0.001150707	3.14	2.63
7	0.9588528×10^{-4}	3.37	3.0
8	-0.1109040×10^{-6}	3.75	4.0
9	0.1264403×10^{-9}	4.0	5.0

Molar Mass : M = 2.01588g/mol
Universal Gas Constant : R = 8.314472 J/(mol·K)

The purpose of using pressure method in this research is to evaluate the possibilities of measuring hydrogen consumption by using hydrogen tanks which is in the FCVs. Therefore, in this research, the hydrogen consumption was measured by pressure and temperature sensors which are same version of sensors attached on the hydrogen tanks in the testing vehicle. The specifications of pressure and temperature sensors on the hydrogen tanks are shown in the Table 4.

Table 4. Specification of pressure & temperature sensor for pressure method

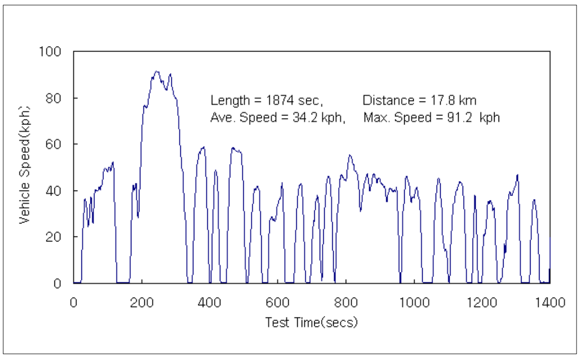
Pressure Sensor	
Range	0 ~ 35MPa
Accuracy	< ±1.0% of BFSL.
Response Time	10 ms

Temperature Sensor	
Range	-50 ~ 150 ℃
Accuracy	± 2 % of F.S.
Linearity	± 1 % of F.S.

2.2 Driving Schedule

3 Driving Schedules of U.S. EPA was used for a fuel economy measurement test of FCVs. Urban Dynamometer Driving Schedule(UDDS) is composed to two phase of driving simulation in the downtown and Highway Fuel Economy Test Driving Schedule (HWFET) is a driving simulation on the high way under 97km/h. Federal Test Procedure (FTP) has a driving schedule which drives UDDS and then drives again the first phase of UDDS. In Korea, the driving schedule which is same with FTP is used for the fuel economy measurement test.

In this research, the test was conducted with UDDS as the primary driving schedule and two driving schedules of HWFET and FTP were also used to confirm the compensated results of the hydrogen flow sensor. Figure 4 is showing simple explanation of UDDS and HWFET.



< Urban Dynamometer Driving Schedule>

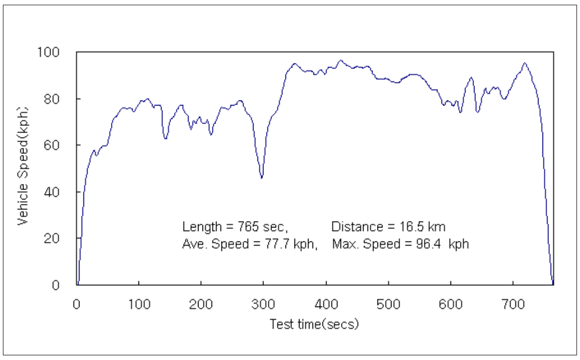


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Figure 4. Driving Schedule of fuel consumption measuring of FCV[7]

2.3 Measurement System

The hydrogen fuel economy measurement equipment was developed as Figure 5. So that three methods : gravimetric method which is the basic measurement method, flow method which is to measure real-time hydrogen consumption and pressure method which is to evaluate the possibilities of hydrogen consumption measuring by using hydrogen tanks that is equipped on the FCVs, performs at one measurement system at the same time.

Figure 5. Hydrogen fuel economy measurement system

The hydrogen fuel economy measurement equipment was composed of weight balance and flow sensor which are introduced above, and pressure and temperature sensors which are equipped on the hydrogen fuel tanks. It is also deigned to be able to select as automatic or manual in the processes from the beginning and to the end of the test. The diagram of the measurement equipment is shown in the Figure 6.

3. Fuel Economy Test Results

ISO standard, SAE standard and various researches were conducted regarding the hydrogen measurement of FCVs. So, in this research, as the review of the previous research, gravimetric method which can get the most stable measurement results, was selected as the primary measurement method. flow method was used for the real-time measurement and the pressure method was use to evaluate the direct use of hydrogen fuel tanks which is equipped on the testing vehicle. And both methods were performed the measurements with gravimetric method at the same time. U.S. UDDS was use as driving schedule for this test and the FCV(FY2008) which is produced in Korea was used as the testing vehicle. For the testing fuel, hydrogen purge line which is the lower part of the FCV was modified as shown in the Figure 7, and the hydrogen was supplied from external hydrogen

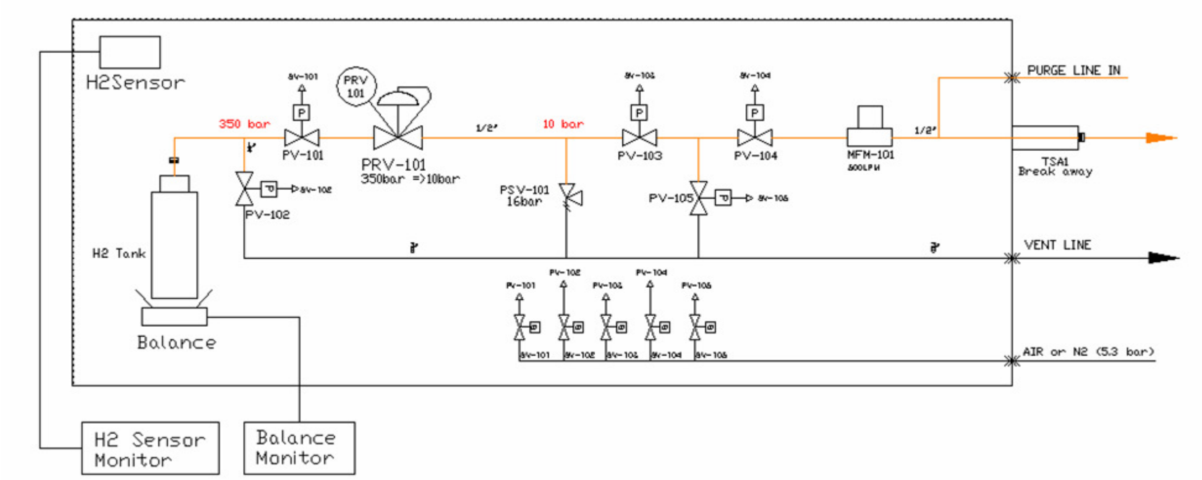

Figure 6. Schematic diagram of hydrogen fuel consumption testing system

fuel supply device through the connected modified part. Figure 8 shows the feature of fuel economy measurement tests for the FCV.

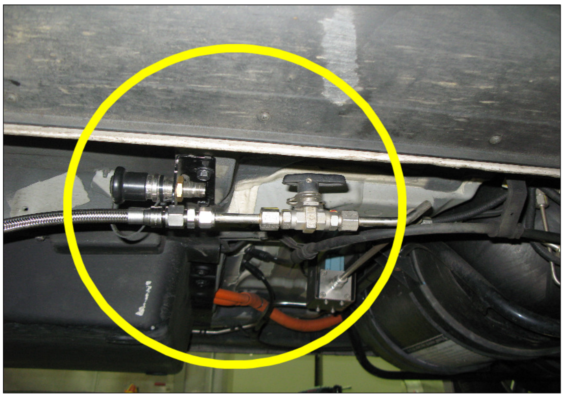

Figure 7. External Hydrogen fuel supply connection

Figure 8. Hydrogen fuel cell vehicle fuel economy test

3.1 Accuracy Verification of Gravimetric Method

Before the fuel economy measurement, in order to verify the adequacy and the reliability of the weight balance using in the gravimetric method, indicating reproducibility for the measurement and the accuracy of measurements for the changes of weight was confirmed by using the standard weight which has similar weight of hydrogen tanks in the test. The verification of accuracy and reproducibility for gravimetric method showed very good results and it is shown in the Table 5.

Table 5. The results of accuracy verification about weight balance

Standard weight(g)	W_1 (0.65)	W_2 (19,997.7)	W_1+W_2 (19998.35)
Mean	0.65	19,997.73	19,998.39
Std. Dev.	0.0122	0.0114	0.0155
Std. Err.	0.0031	0.0028	0.0039
Size	16	16	16
Min.	0.64	19,997.72	19,998.37
Max.	0.68	19,997.76	19,998.43

3.2 UDDS Test Results

As the result of the Fuel economy measurement test for the Hydrogen Fuel Cell Vehicle by using UDDS, the standard deviation of each measurement methods are calculated as shown in the Figure 9. The standard deviation of the result using gravimetric method which is the primary measurement method in this research was 0.9%. So, it appeared that its reproducibility of the measurement result is excellent. However, in the case of pressure method, the standard deviation was 2.5% which means it is unstable than gravimetric method. The reason of this deviation is that it did not consider the above premises which are soaking time and the accuracy problems of the pressure and temperature sensors regarding the use of hydrogen fuel tank equipped on the vehicle.

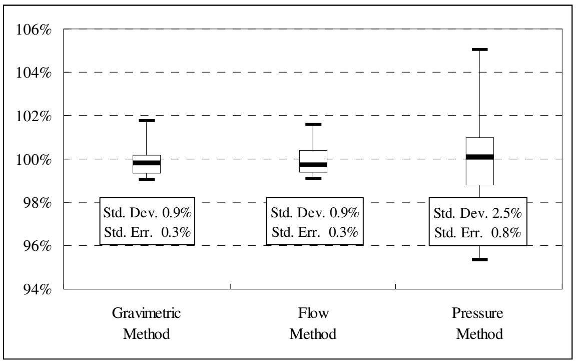

Figure 9. Standard deviation & Error of each test method

In the case of flow method, the standard deviation of the measurement results is 0.9% which

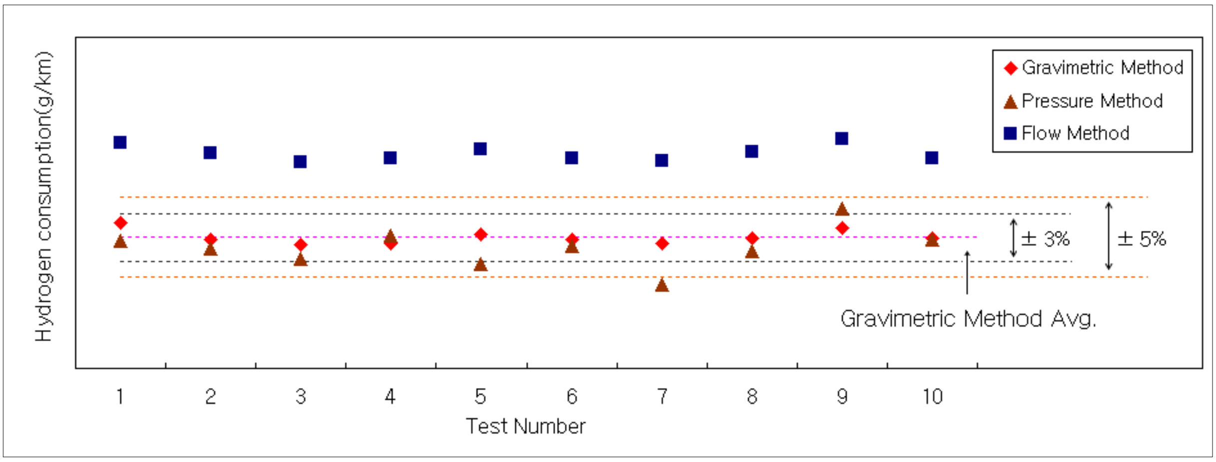

Figure 10. Test result of fuel consumption test(UDDS)

is similar with gravimetric method. So it is excellent in the matter of the reproducibility of the measurement result. But as seen in Figure 10, the absolute value of the measured value is constantly higher than gravimetric method. It is considered that it is caused by the revision errors of hydrogen flow sensor in this sensor. Re-correction by the sensor manufacturers or compensation in the testing site with the result of gravimetric method can be solutions for that. Re-correction by the sensor manufacturers needs time and costs. On the other hand, it has a benefit that hydrogen flow sensor can be compensated in short time, in the case of compensating it in the testing site. Accordingly, this research separately verified the compensation for flow method results using gravimetric method results in 3.3.

In Korea, certification for fuel economy measurement of a newly manufactured vehicle is granted when results of fuel economy measurement which is provided from vehicle maker and result of certification exam are in ±3% variance, and in case a mass-produced vehicle, the variance is set as ±5%. Therefore, according to the result of figure 10, gravimetric method is appropriate for measurement of certification. However, pressure method using pressure and temperature sensor which is equipped in hydrogen tank in basic without soaking time after test is not suitable for certification test method. But generally to assess FCVs performance on real roads, not in test room, or for test which is not required precise measurement relatively, it's thought to be possible pressure method is appropriate. And if reproducibility of measure result is guaranteed, measurement accuracy for certification test would be secured through correcting and compensating by hydrogen flow sensor.

To cover defect of gravimetric method which is not able to measure the consumption of hydrogen fuel in real-time, the measurement of consumption of hydrogen fuel in real-time measured by flow method is same as figure 11. In this research, it was tried to measure changes of weight when in progress tested by gravimetric method. The result tested by flow method and gravimetric method are showing similar pattern and it's possible to recognize general tendency of fuel consumption in gravimetric method in real-time.

3.3 Compensating Flow method and Verifying Test.

As result in 3.2, flow sensor using in this research over-measured consumption of hydrogen fuel than result in gravimetric method by certain amount. Therefore hereby we recognize correlation

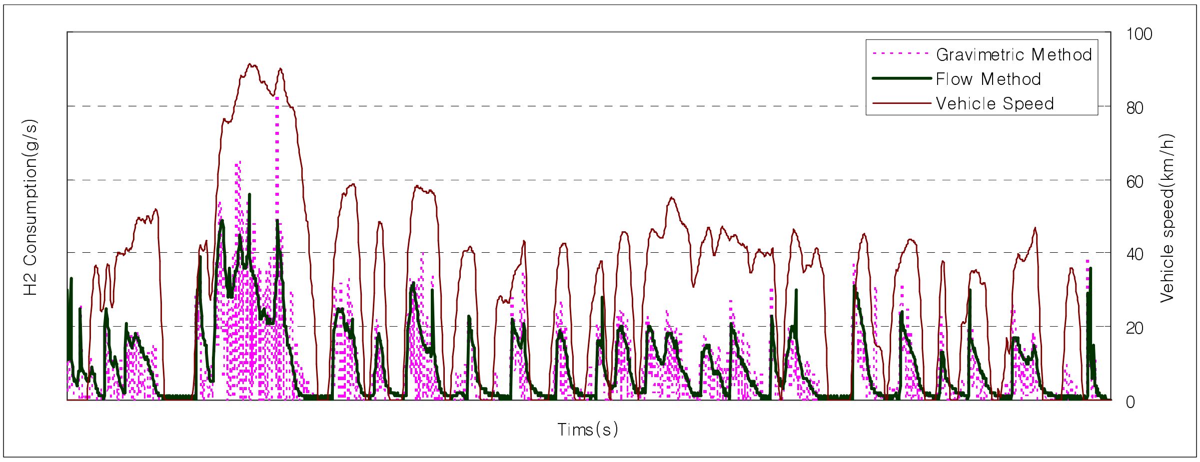

Figure 11.Real-time fuel consumption measured by UDDS

between gravimetric method and flow method, and compensate the result of flow method using linear regression analysis. Amount of hydrogen for correction is set as 50g, 100g, 150g, and 200g, for each setting weight is tested 10 times and using the result for compensation. Hydrogen fuel is not flowed regularly until certain range of weight, but it was made to flow in random. When Fuel Cell Vehicle is on the road, fuel is not supplied regularly but changeable, test is executed to simulate in real condition, The measure result of each hydrogen test set is same as figure 12.

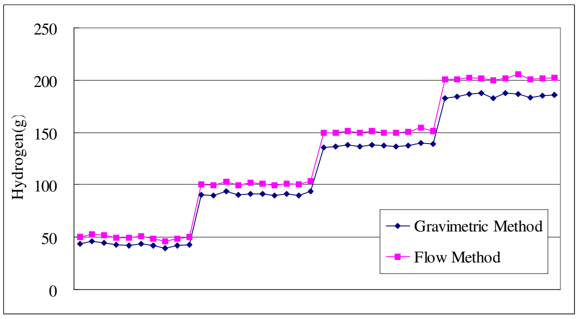

Figure 12. Measuring result by hydrogen fuel amount used (Gravimetric method & Flow method)

As the result of the linear regression analysis by using the measurement results for the each setting weight, the Coefficient of Determination (R^2) was superior as 0.99976, and the linear regression formula was calculated as Eq.(5). Figure 13 is the result of the linear regression analysis.

$$Y = -3.54449 + 0.93637X \tag{5}$$

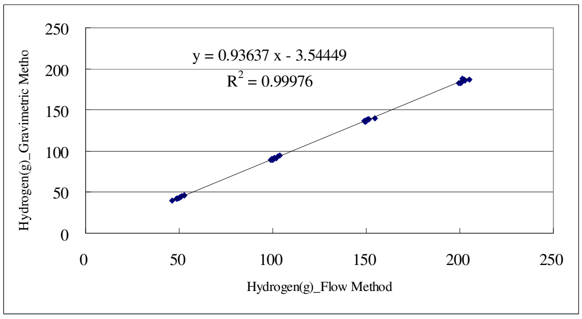

Figure 13. Linear regression analysis result

The UDDS measurement result was used to verify the suitability of linear regression analysis, and in addition, the compensated result was confirmed by conducting a test using HWFET and FTP one more time. Before the compensation, the measurement result in the gravimetric method had about 10% of deviation, but after the compensation, it showed a better result that the measurement value became less than 1%. Table 6 shows the result of measurement before and after the compensation.

Table 6. The result of Hydrogen fuel consumption compensation about flow method

Driving Schedule	No. of test	Deviation before compensation (vs. gravimetric method)	Deviation after compensation (vs. gravimetric method)
UDDS	1	9.92%	-0.10%
	2	10.85%	0.70%
	3	10.58%	0.43%
	4	10.85%	0.69%
	5	10.77%	0.65%
	6	10.24%	0.14%
	7	10.48%	0.35%
	8	10.83%	0.69%
	9	10.98%	0.87%
	10	10.06%	-0.03%
HWFET	1	8.30%	-0.63%
	2	8.99%	0.01%
	3	7.95%	-0.96%
FTP	1	8.89%	0.10%
	2	9.35%	0.52%

4. Conclusion

FCVs currently are not sold through mass production yet, but it is expected that mass production system will be equipped in the near future to meet consumer's demands. Hence, various measurement methods and studies are conducting on that to deliver reliable fuel economy information regarding FCVs for customers. Consequently, fuel economy measurement methods of FCVs are condensed into three kinds of methods: gravimetric method, flow method and pressure method. And their accuracy are already proven. However, FCVs are not in the mass-productions system. Possible problems are not clear which will happen when those methods are applied to the real mass-produced FCVs. Therefore, this research measured the fuel economy of FCVs in easy and exact ways based on the previous study results. For each methods, the efforts has been made to meet applicability of new aspects which are different from previous researches. For that reason, the reliability was verified by deciding gravimetric method as a primary method, because it has the least variables. And also, the evaluation for another applicability of each method was conducted.

The results of this research are as follows.

- In the case of measuring the amount of fuel consumption disregarding soaking time with pressure and temperature sensors which are equipped on the hydrogen fuel tanks in basic, the accuracy of results was not as good as gravimetric method. But its measurement deviation was about ±5%. When we consider the benefit that it is possible to apply measurement method without structure change of testing vehicles, if the fuel economy tests on the road or relatively precise measurements are not required, it is worth to consider about its uses.

- In the case of gravimetric method, this research has confirmed the possibilities of real-time measurement of the amount of hydrogen consumption as flow method, though it is still approximate.

- In flow method, the reliability is able to verify if the deviation of the measurement result in the same condition is small. So it can compensate the result of the measurement with linear regression analysis by using other measurement results. This research has confirmed that the deviation decreased from 10% to 1% after the compensation.

5. Future work

Three measurement methods which are verified by ISO and SAE etc, its accuracy was already secured. But in the case of the three measurement methods for FCVs, the biggest defect is that the external fuel supplying system has to be connected to the testing vehicle to measure fuel economy.

This research also applied the same way. But for the connection with the testing vehicle, it is needed to modify some parts of the vehicle. Consequently, it could have some criticism regarding the modifying ways and connecting ways of the testing vehicle if apply the measurement method by external fuel supply system to the fuel economy test in the developments of variety Hydrogen Fuel Cell Vehicles. Therefore, KATRI is planned to conduct studies on the new measurement methods which does not need to modify the testing vehicles through standardization of testing vehicle and the ways of connecting external fuel supply system, or by using the flow, pressure and temperature sensors which are equipped on the testing vehicle.

Acknowledgments

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