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Development and evaluation of the calibration facility for high-pressure hydrogen gas flow meters

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ABSTRACT

The calibration facility with the multi-nozzle calibrator was developed for the calibration of flow meters to be used with high-pressure, high-flow-rate hydrogen gas. The critical nozzles installed in the multi-nozzle calibrator were calibrated with traceability to the national standard. The relative standard uncertainty of the mass flow rates produced from the calibration facility is 0.09% when the flow rate is between 150 g/min and 550 g/min. In this study, the Coriolis flow meter was calibrated for a pressure range of 15–35 MPa. The relative standard uncertainty of the flow rates obtained from the Coriolis flow meter was 0.44% for the case of the worst fluctuations in the output of the flow meter; based on the calibration curve, this is 0.91%. The present result shows that there is a maximum 3% difference between the output of the Coriolis flow meter and the mass flow rates of the multi-nozzle calibrator, even though the Coriolis flow meter was calibrated using water. Therefore, for the development of a calibration facility that can calibrate a flow meter under the same conditions as those encountered in actual use, it will be important to develop a new flow meter.

1. Introduction

As one of the measures to reduce CO_2 emissions for addressing global warming, as well as to address other energy issues, transition to next-generation vehicles is proceeding at a rapid rate. Among the next-generation vehicles, fuel cell vehicles (FCVs) and electric vehicles (EVs) are considered very promising. An FCV emits no hazardous air pollutants, in particular, no NO*x*, CO_2, or suspended particulate matter. Hydrogen gas used as fuel for an FCV can be produced from various energy sources, such as natural gas, sunlight, wind power, and biomass, so it has a high potential for reducing oil dependence and CO_2 emissions. Therefore, various research and development projects and tests of FCVs are currently being implemented both in Japan and elsewhere [1–8].

In July 2010, the Fuel Cell Commercialization Conference of Japan (FCCJ) announced a goal of making FCVs and hydrogen stations available in the consumer market by 2015, and to begin to establish hydrogen supply infrastructure in order to pave the way for the active commercialization of FCVs [9]. To achieve this goal, it is necessary to overcome numerous technological challenges[10–13], to revisit relevant regulations[2], and to facilitate international standardization [14]. One of the challenges is to develop a technology by which hydrogen gas can be added to the fuel tank of an FCV. Various additional goals have been specified regarding longer cruising distances, safety guidelines, and relevant legislation; these include a maximum filling pressure of 87.5 MPa, a maximum filling flow rate of 3.6 kg/min, a pre-cool temperature of −40 °C, and introduction of a communication device to be used for filling the tank [9].

The fuel tank of an FCV is filled with hydrogen gas at a hydrogen station. The flow meter used at the station is classified as a measuring instrument for commercial trade, and therefore it must be extremely reliable, must produce consistent measurements, and must have long-term stability. With this in mind, Nakao et al. [15,16] and the authors [17] have developed a critical flow meter to measure high-pressure hydrogen gas; this nozzle meter has no moving parts, features outstanding reproducibility, and has been evaluated at the facilities of private companies, which can supply hydrogen gas at 35 MPa and 70 MPa. However, these facilities did not have any instruments to measure the gas flow rates, and as far as the authors know, there are few calibration facilities [18] anywhere that can supply high-pressure hydrogen gas with an instrument that can reliably measure the flow rate.

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When evaluating a commercially used flow meter at a calibration facility, it is desirable to be able to accurately measure the flow rate, and, if possible, these instruments should be calibrated with national or even international standards.

Our research group has been engaged in the development of a calibration facility for supplying hydrogen gas flow at a pressure of 35 MPa and with the calibrator traceable to the national standard [19]. This article presents the details of the calibration facility, including an uncertainty analysis, and the results are presented for a Coriolis flow meter calibrated at this facility.

2. Calibration facility for high-pressure hydrogen gas flow meters

2.1. Outline of the calibration facility

Fig. 1(a) shows a photograph of the calibration facility for high-pressure hydrogen gas flow meters that was developed by our research group and built by the Iwatani Industrial Gases Corp., and Fig. 1(b) shows the flowchart for the system. The calibration facility is composed of 40 MPa gas storage cylinders, an automatic pressure controller (APC), the device under test (DUT), a needle valve, and a multi-nozzle calibrator. The DUT and the multi-nozzle calibrator are housed in the “Test Box” shown in Fig. 1(a). The inset in the lower-left of Fig. 1(a) shows the “Test Box” with its door open. Hydrogen gas initially flows out from the gas storage cylinders at a pressure of 40 MPa, and its pressure is adjusted by the APC to the calibration pressure of the DUT. After flowing through the DUT, the pressure upstream of the multi-nozzle calibrator is regulated by the needle valve so that it does not exceed 700 kPa. After flowing through the multi-nozzle calibrator, hydrogen gas is released to the atmosphere through an exhaust stack with a flame arrestor. The gas storage cylinders of the calibration facility are equipped with fire-prevention equipment that is capable of spraying water at a rate of 108 L/min continuously for about 46 min, in accordance with the Japanese High-Pressure Gas Safety Law.

2.2. Gas storage unit

Table 1 shows the specifications of the gas storage unit installed in the calibration facility. Its maximum storage pressure for hydrogen gas is 40 MPa, it has a storage capacity of 3000 L (250 L gas storage cylinder × 12), and it can provide hydrogen gas for about 10 min at 35 MPa and 550 g/min. This is the maximum flow rate that can be measured by the multi-nozzle calibrator. Each gas cylinder is filled with 40 MPa hydrogen gas by the portable liquefied-hydrogen station developed by Kansai Electric Power Co. and Iwatani Industrial Gases Corp. [20].

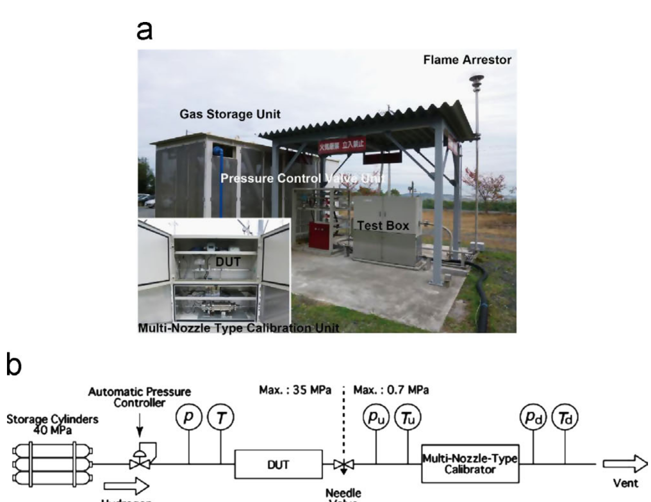

Fig. 1. Configuration of the calibration facility for 35 MPa high-pressure hydrogen gas flow meters. (a) Photograph and (b) flow diagram.

Table 1
Specification of gas storage unit.

Storage gas	Hydrogen
Max. storage pressure	40 MPa
Storage volume	3000 L (250 L × 12 cylinders)
Cylinder dimensions	φ355 mm × L4,900 mm
Cylinder material	SCM435
Unit dimensions	W5.6 m × L2.5 m × H3 m
Unit weight	21,000 kg

2.3. Multi-nozzle calibrator

Fig. 2 shows photographs of the multi-nozzle calibrator, and its specifications are listed in Table 2. The inlet of the multi-nozzle calibrator is on the left side in Fig. 2(a). The flow velocity of the gas is kept uniform by means of two rectifying nets that the gas passes through prior to entering the cylindrical section. A thermometer (T_u) is inserted in the cylindrical section. The four pressure taps are located along the circumference of the cylindrical section, and they are connected by the grooves machined in the wall of the cylindrical section, which looks like a flange in Fig. 2(a), and finally to the tube on the bottom of the cylindrical section. A pressure transducer (P_u) is mounted at the end of the tube. Nozzle holders are on the flange, which is marked by white arrows in Fig. 2(a), and ten critical nozzles can be mounted on it, as shown in Fig. 2(b). A pipe is connected to the outlet of each nozzle, and a pneumatic shut-off valve is mounted on the pipe so that there are ten pairs of pipes and pneumatic valves downstream from the nozzle holder. Hydrogen gas flowing out from the ten pipes is confluent in the downstream chamber, and flows downward. A pressure transducer (P_d) is mounted at the downstream chamber to measure the pressure downstream from the nozzles. Since each critical nozzle is calibrated by the NMIJ/AIST's primary standard [22] at pressures from 100 kPa to 700 kPa, the pressure upstream from the calibrator is maintained by the needle valve at less than 700 kPa.

The critical nozzles mounted on the nozzle holders of the multi-nozzle calibrator are disc shaped, as shown in Fig. 2(b), and a nozzle is machined into the middle of each disc. The nozzles are toroidal-throat Venturi nozzles, as specified in ISO 9300 [21]. The nozzle shape and the throat diameter are measured to a resolution of 1 um. Table 3 shows the parameters of the critical nozzles. In this article, the throat diameter is treated as a constant, and thus it is not considered as a source of uncertainty in the analysis.

The critical nozzles installed in the multi-nozzle calibrator are calibrated following the steps specified by the NMIJ/AIST's primary standard [22] and the calibration system (the secondary standard). To begin, several critical nozzles were calibrated to the primary standard, using hydrogen gas. The maximum flow rate was about 60 g/min. These critical nozzles, the working standard nozzles, were installed in the calibration system to calibrate the critical nozzles installed in the multi-nozzle calibrator, which were calibrated with hydrogen gas for a maximum flow of 110 g/min.

Fig. 3 shows the discharge coefficient (Cd) values for the five critical nozzles installed in the multi-nozzle calibrator, which were calibrated by the above method. The definition of the discharge coefficient is

$$Cd = Q_m / Q_{mth} \qquad (1)$$