Inter-laboratory Comparison of Small Water Flow Calibration Facilities Between EHJ and NMIJ

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Abstract

Comparison between facilities at Endress+Hauser Japan and NMIJ was carried out according to three transfer standards, using a Coriolis flowmeter. The range of flowrate was from 30 kg/h to 36000 kg /h. Comparison results showed excellent agreement for both standards, at less than 0.018%. *En* values are also less than 0.52 for all examined flowrate points. These results demonstrate the consistency of facilities at both labs.

1. Introduction

Recently, advanced flowrate management is required in many fields from the micro level to the large plant level. Advanced flowrate management has many advantages such as improved product quality, energy savings, etc. As requirements to reduce environmental burden become stricter, the importance of highly accurate flowrate measurement has increased. With this background, development of highly accurate flowmeters is urgently needed. Small water flowrate, within the order of 1 kg/h to 105 kg/h is no exception. Many fields, including bio, chemical, semiconductor, food, etc. require a highly accurate flowrate measurement. Needless to say, the need for highly accurate, low uncertainty calibration facilities is growing at the same time [1][2].

Responding to the need for small flowrate calibration, AIST, NMIJ (hereafter, NMIJ) has developed several small liquid flow calibration facilities for water and hydrocarbon [3][4]. In this paper we focus on small water flowrate calibration facilities. The developed small water flowrate calibration facilities are applicable from 2 kg/h to 1,200 kg/h using a single weighing tank system. The uncertainty for mass flowrate based on the static gravimetric method is estimated to be 0.034% with coverage factor k=2. NMIJ also has a 350 kg weighing tank system with 0.038% (k=2) uncertainty for small flowrate from 300 kg/h to 35,000 kg/h [3]. Uncertainties of these facilities are sufficiently low for calibration of general flowmeters. However, for highly accurate flowmeters, a lower uncertainty level of the calibration is necessary. In the first step of this paper, uncertainty of the small water flowrate facilities at NMIJ is re-evaluated to achieve actual flow calibration with low uncertainty.

The most significant aspect of this study is an inter-laboratory comparison between different small water calibration facilities with extremely low uncertainty. The BIPM organizes international comparison programs. The CCM-WGFF key comparison program, for water flowrate CCM-FF.K1 was carried out in 2004 [5]. A second round began in 2015. In local regions including Japan, APMP key comparison was also performed for water flowrates in 2009 [6]. In these comparisons, the range of tested flowrate was large, up to the order of 102 kg/h. These comparisons are very important to obtain consistency in international flowrate measurements. NMIJ participated in these comparisons and obtained results which were consistent with those from other labs as can be seen in the cited comparison reports.

In this paper, a bilateral inter-laboratory comparison between two facilities for small water flowrate is performed between Endress+Hauser Japan co. Ltd. (hereafter, E+H-J) and NMIJ. The expanded uncertainty of this comparison is around 0.02% with k=2.

2. Facilities at NMIJ

2.1 Overview of facilities

An aerial view of the small flowrate facility with a 10 kg weighing tank system is shown in Fig.1. Hereafter, this facility is referred to as “the 10 kg system”. In principle, the working fluid, water, is supplied to the test line by pumps. Two type of management flowmeters, namely electromagnetic and Coriolis flowmeters are installed upstream from the chamber. In the chamber, a flow conditioner is installed. The chamber and the flow conditioner eliminate disturbance of the velocity profile due to the Coriolis flowmeter. Test lines are located downstream from the chamber. Inlet flow of the test section is carried out by a reducer. This facility has two test lines with base pipe diameters of DN15 and DN25. Flowrate ranges in each line are 2 kg/h -40 kg/h and 10 kg/h -1,200 kg/h, respectively.

A weighing tank system with the diverter is installed downstream of the test lines. A rotating diverter system is used in this facility [7]. Since the rotating diverter system is double wing type [8], timing error caused by the diverter error can be zero in principle. Four flow nozzles are located on the concentric circular and are selected depending on flowrate. Capacity of the weighing tank is approx. 0.012 m^3. This tank has a lifting system. While accumulating water, the weighing tank is lifted and completely attached to the diverter room. In this way, if the diverter room and inside of the tank are occupied by vaporized air, the effect of evaporation can be avoided. Humidity in the diverter room is measured during the measurement.

The test line is covered by an insulator. Water temperature can be controlled from 10 °C to 40 °C using the temperature control unit and heat exchanger. The temperature fluctuation during measurement is less than 0.1 °C for flowrates larger than 100 kg/h. Pressure can be controlled around 0.2 MPa±0.02 MPa.

To avoid fluctuation in flowrate, an in-line accumulator is installed downstream from the pumps. Moreover, working fluid can be supplied to the test section from the overflow head tank at a height of 30 m. Fluctuation in flowrate measured by Coriolis flowmeter is less than 0.1%.

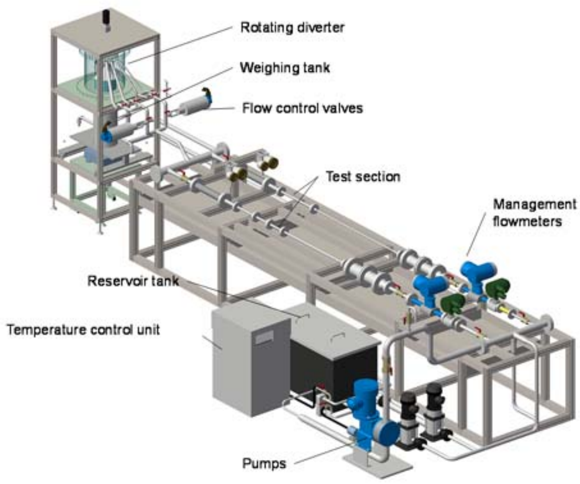

Figure 1: Facility of 10 kg weighing tank system at NMIJ.

An aerial view of the 350 kg weighing tank system is shown in Fig.2. Hereafter, this facility is referred to as "the 350 kg system". This facility is completely separated from the facility with the 10 kg system. Water is supplied from the overflow head tank at 30 m height. Main test lines consists of DN100 and DN50. The upstream straight pipe length is over 100 times that of the inner diameter of pipe. An electromagnetic management flowmeter is installed upstream of the test section.

The diverter of the weighing tank system is double wing type [7]. Mechanical properties of this diverter are the same as a rotating type, but the diverter is one directional. As mentioned, timing error of a double wing type diverter can be zero in principle. Width of the nozzle is automatically controlled to avoid splash of the working fluid. A lifting system of the weighing tank is also installed.

Water temperature is controlled at 20 °C ±5 °C using a chiller system and temperature fluctuation during the duration time is ±0.2 °C. Pressure is dependent on flowrate and is between 0.10 MPa to 0.24 MPa.

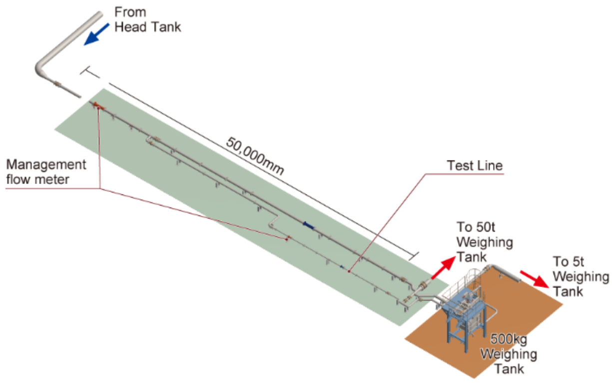

Figure 2: Facility of 350 kg weighing tank system at NMIJ.

2.2 Re-evaluation of uncertainty

To calculate mass flowrate q_m using the weighing tank system, the following simplified model is used.

$$q_{\mathrm{m}} = \left(\frac{M_{\mathrm{T}}}{1 - \rho_{\mathrm{air}} / \rho_{\mathrm{wT}}} + \Delta M_{\mathrm{C}} \right) \Big/ \left(t_{\mathrm{D}} + \Delta e \right) \qquad (1)$$

where, M_T is the mass of the water in the weighing tank and ΔM_C is the correction of the mass due to temperature fluctuation in the pipeline and dead volume. ρ_{air} is the density of air surrounding the tank, ρ_{wT} is the density of the water in the tank. $1-\rho_{air}/\rho_{wT}$ is the correction of buoyancy. t_D is the time measured by the timer and Δe is the correction time for the diverter timing error. The numerator of Eq.(1) is the mass which passes through the test meter and the denominator is the duration time.

In the previous paper, the expanded uncertainty of the facility is estimated to be 0.034% for 10 kg system and 0.038% for 350 kg system[3]. This uncertainties are determined to do the general calibration work. In this paper, it is called as the general operation. On the other hand, the uncertainty for the bi-comparison with E+H-J is determined as the special operation. The details of the uncertainty estimations are explained in the following sections.

2.2.1 Uncertainty of duration time

Uncertainty of the time measurement is determined by the following formula.

$$u(t) = \sqrt{u(t_{\mathrm{D}})^2 + u(\Delta e)^2} \qquad (2)$$

$u(t_D)$ is the uncertainty of measurement of time and $u(\Delta e)$ is the timing error of the diverter. Uncertainty of measurement of time is estimated as the uncertainty of the timer. Uncertainty of the timer is estimated to be 0.0006%, taking into account accuracy, temperature effect, reproducibility and calibration of the timer.

Timing error of diverter is estimated according to ISO-4185 [9]. Timing error caused by the un-axisymmetric velocity profile of water flow from the nozzle can be zero in principle using the double wing diverter. The external trigger to start and stop the measurement of time is synchronized with the motion of the diverter using the optical sensors on the micro traverses. The position of the optical sensors are adjusted to obtain minimum timing error. Detail are described in the previous paper [7][8]. As the final result, timing error is estimated to be 0.3 msec for the 10 kg system and 1.21 msec for the 350 kg system. Since the minimum measurement time is 30 sec. and 39 sec., respectively, relative uncertainty of the time measurement is estimated to be 0.0010% and 0.0031%.

By combining the uncertainties of the timer and the timing error, uncertainty of the duration time is estimated to be 0.0012% and 0.0032% for the 10 kg and the 350 kg weighing tank systems, respectively.

2.2.2 Uncertainty of mass passing through the test meter

Uncertainty sources of mass measurement in the weighing tank are the specifications and the calibration of scale. The dominant uncertainty sources of the specifications of the scale are linearity, temperature effect, time-dependent drift, reproducibility and eccentricity. The uncertainty sources of resolution, repeatability and the reference weight are negligibly small. Under general operation, the temperature of the air surrounding the weighing tank is maintained at 20 °C ±7.5 °C and time-dependent stability is estimated to cover 1 g for the 10 kg system and 20 g for the 350 kg system. These two factors are the dominant uncertainty of scale after calibration. In this experiment, the temperature of the surroundings of the weighing tank is maintained within ±2.5 °C and time-dependent stability is reduced to negligible levels by calibrating in a short period. The uncertainty of the calibration is estimated according to the guidelines presented by EURAMET [10] and were set as 1.03 g for the 10 kg system and 39.01 g for the 350 kg system.

Uncertainty of buoyancy correction is estimated to be 0.070% in general operations. Although air temperature, atmospheric pressure and humidity are measured during general operations, uncertainty of air density is estimated assuming that these values are not measured. Therefore, uncertainty is a dominant factor of the facility in general operations. In this experiment, actual measurement results of atmospheric pressure, air temperature and humidity are reflected in the uncertainty evaluation. Standard uncertainty of air density is estimated to be 0.0039 kg/m^3. Water density is calculated using the following density correction.

$$\rho_{wT} = \rho_{pw}(T) - \rho_c \tag{3}$$

where, ρ_{pw} is the density of pure water, T is water temperature and ρ_c is the correction of density. ρ_c is obtained by a density meter calibrated by the density standard water. Standard uncertainty of the density of water is estimated to be 0.029 kg/m^3. As a result, relative standard uncertainty of buoyancy correction is estimated to be 0.0006% which is negligible.

Mass is adjusted by the following equation.

$$\begin{aligned}\Delta M_C &= \Delta M_{DV} + \Delta M_{SL} \\ &= \Delta\rho_{wD} V_D + \Delta\rho_w V_{SL}\end{aligned} \tag{4}$$

where, V_D is dead volume and V_{SL} is the volume between the test meter and the diverter nozzle, namely the stream line. These volumes are calculated by the inner diameter and the length of the pipe. V_D is 1.04×10^{-3} m^3 for the 10 kg system and almost zero for the 350 kg system. V_{SL} is 2.33×10^{-3} m^3 for the 10 kg system and the 1.25×10^{-1} m^3 for 350 kg system. $\Delta\rho_{wD}$ and $\Delta\rho_w$ are the change in the density of water in dead volume and the stream line, respectively, during measurement. Change in density is dependent on temperature change. During measurement, water temperature in the dead volume is less than 0.5 °C and less than 0.1 °C in the stream line for 10 kg and 0.2 °C for 350 kg system, as mentioned.

Uncertainty caused by correction of mass is estimated by the following equation.

$$u(\Delta M_C) = \sqrt{\begin{aligned}&\{V_D u(\Delta\rho_{wD})\}^2 + \{\Delta\rho_{wD} u(V_D)\}^2 \\ &+ \{V_{SL} u(\Delta\rho_w)\}^2 + \{\Delta\rho_w u(V_{SL})\}^2\end{aligned}} \tag{5}$$

Uncertainty of both volumes is estimated to be roughly 1% based on the experience of the measurement. Uncertainty of change in density for the 10 kg system is estimated to be 0.06 kg/m^3 for $\Delta\rho_{wD}$ and 0.01 kg/m^3 for $\Delta\rho_w$. For the 350 kg system, change in density is 0.02 kg/m^3 for $\Delta\rho_w$. As a result, standard uncertainty of mass correction is estimated to be 0.06 g for the 10 kg system and 3.0 g for the 350 kg system. Relative uncertainty is estimated to be 0.0007 % and 0.0009% and is negligible.

2.2.3 Budget sheet

To summarize re-evaluation of uncertainties, budget sheets for the 10 kg and 350 kg systems are shown in Table 1. The expanded uncertainty under general operations is estimated to be 0.034% for the 10 kg system and 0.038% for the 350 kg system with k=2. On the other hand, the expanded uncertainty in this paper is estimated to be 0.021% for the 10 kg and 0.023 % for the 350 kg systems with k=2.

Table 1: Uncertainty budget sheet for 10 kg and 350 kg weighing tank systems at NMIJ.

	10 kg*1		350 kg*2	
Uncertainty source	General	Present	General	Present
Duration time	**0.0012%**	**0.0012%**	**0.0032%**	**0.0032%**
Timer	0.0006%	0.0006%	0.0006%	0.0006%
Timing error	0.0010%	0.0010%	0.0032%	0.0032%
Mass passed in DUT	**0.0170%**	**0.0103%**	**0.0189%**	**0.0112%**
Scale	0.0152%	0.0103%	0.0176%	0.0112%
Buoyancy correction	0.0070%	0.0006%	0.0070%	0.0006%
Mass correction	0.0007%	0.0007%	0.0004%	0.0004%
Standard uncertainty (u_c)	**0.0170%**	**0.0104%**	**0.0192%**	**0.0117%**
Expanded uncertainty ($2u_c$)	**0.034%**	**0.021%**	**0.038%**	**0.023%**

*1. 30 kg/h - 1200kg/h
*2. 500 kg/h - 36000 kg/h

3. Facility at E+H-J

A schematic diagram of the calibration facility at E+H-J is shown in Fig. 3. The facility has two reference standards, the cylinder system and the weighing tank system. For small flowrates less than 1.08 m^3/h, the reference standard is the volumetric cylinder of 10 L. For flowrates larger than 1.08 m^3/h, the reference standard is the weighing tank system. The capacity of the weighing tank is 400 kg and the diverter system is a single wing type. Hereafter, the 400 kg weighing tank system at E+H-J is referred to as the 400 kg system. Within the overlapping flowrate range, calibration testing can be carried out by both references. Temperature stability of the water is less than ±0.0092 °C. The pressure of the facility is 0.1 MPa– 0.5 MPa.

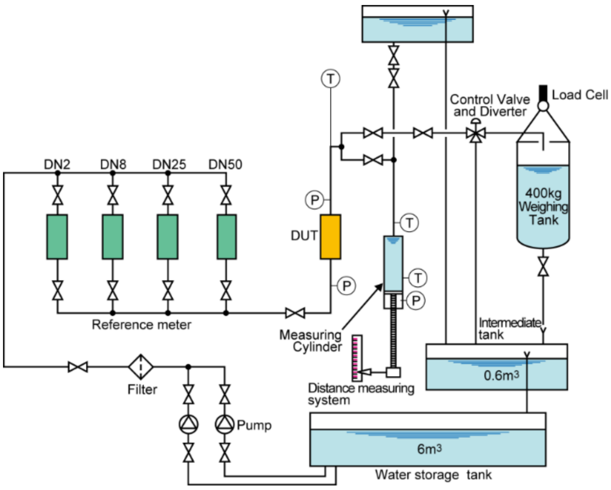

Figure 3: Flow sheet of calibration facility at E+H-J.

The uncertainty budget sheet is shown in Table 2. Basic procedures to estimate the uncertainty analysis for the weighing tank system at E+H-J is same that at NMIJ. Since the effect of dead volume is negligible, uncertainty values are not listed in the table. The dominant uncertainty source is the cylinder constant for the cylinder system and the scale for the weighing tank system.

A low uncertainty of the facility was mainly achieved by frequent calibration of the references. The dead weight is attached with the weighing tank and the scale is calibrated by them automatically. The standard uncertainty of the scale is estimated to be 0.0063%. This uncertainty is smaller than NMIJ although the uncertainties by other sources are same level.

Table 2: Uncertainty budget sheet for the cylinder system and the weighing tank system at E+H-J.

Uncertainty source	Cylinder system*1	400 kg system*2
Cylinder constant	0.0097%	-
Cylinder leak	0.0007%	-
Temperature	0.0011%	-
Water density	0.0038%	-
Scale	-	0.0063%
Buoyancy adjustment	-	0.0012%
Diverter adjustment	-	0.0029%
Impulse	0.0012%	0.0012%
Standard uncertainty (u_c)	**0.0105%**	**0.0071%**
Expanded uncertainty ($2u_c$)	**0.021%**	**0.014%**

*1. 30 kg/h - 1080kg/h
*2. 720 kg/h - 36000 kg/h
Note: CMC which includes the repeatability of the test meter is 0.025% for the cylinder and 0.020% for 400kg weighing tank.

4. Comparison

4.1. Comparison procedure

The comparison range of flowrate is from 30 kg/h to 36,000 kg/h, as shown in Fig. 4. In this comparison, three Coriolis flowmeters, DN02, DN08, and DN50, are used as transfer meters. As mentioned, both labs have two reference standards. NMIJ has two weighing tank systems and E+H-J has one weighing tank system and one cylinder system. DN02 and DN08 are examined using the 10 kg system and DN50 is examined using the

350 kg system at NMIJ. At E+H-J, DN02 and DN08 are examined by the cylinder system and DN50 is examined by the 400 kg system. Next, the 10 kg system at NMIJ and the cylinder system are compared and then the 350 kg system at NMIJ and the 400 kg system at E+H-J are compared using the transfer meters.

Before comparison, reproducibility of the transfer meters was confirmed at NMIJ. After testing at NMIJ, the transfer standard is transferred to E+H-J. Testing is repeated five times for all measurement flowrate points. Details of the comparison is summarized in Table 3.

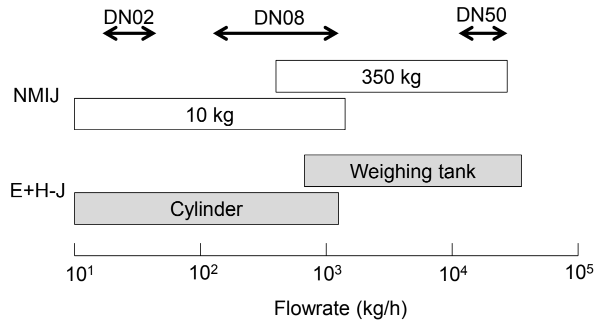

Figure 4: Examined flowrate range in comparison

Table 3: Facility and transfer meter in comparison

Exp. No.	Flowrate range(kg/h)	Transfer meter	Facility at E+H-J	Facility at NMIJ
1	30 – 60	DN02	Cylinder	10 kg
2	120 – 720	DN08	Cylinder	10 kg
3	720 – 1080	DN08	400 kg	10 kg
4	10800 – 36000	DN50	400 kg	350 kg

4.2. Comparison results

Comparison results between E+H-J and NMIJ are shown in Fig. 5 and differences in the results for all transfer meters are shown in Fig. 6. The comparison results demonstrate excellent agreement between two labs. Although there is an approx. 0.02% difference in the results of DN02, the difference is less than 0.01% for DN08 and DN25. As mentioned, uncertainties caused by reproducibility of transfer meters are estimated to be from 0.007% to 0.013%. Since the difference between two labs is at the same level as uncertainty of reproducibility of the transfer meters, the comparison results in this paper show remarkable agreement.

En value for the comparison between E+H-J and NMIJ is given by the following formula.

$$En = \frac{|E_{\mathrm{EHJ}} - E_{\mathrm{NMIJ}}|}{\sqrt{U_{\mathrm{EHJ}}^{2} + U_{\mathrm{NMIJ}}^{2}}} \tag{6}$$

En values in this comparison are shown in Fig. 7. En value is also extremely small although the facilities are constructed based on individual concepts. *En* values are less than 0.5 for DN02, and less than 0.2 for DN08 and DN50. This excellent consistency in the results indicates high performance of the facilities in both laboratories.

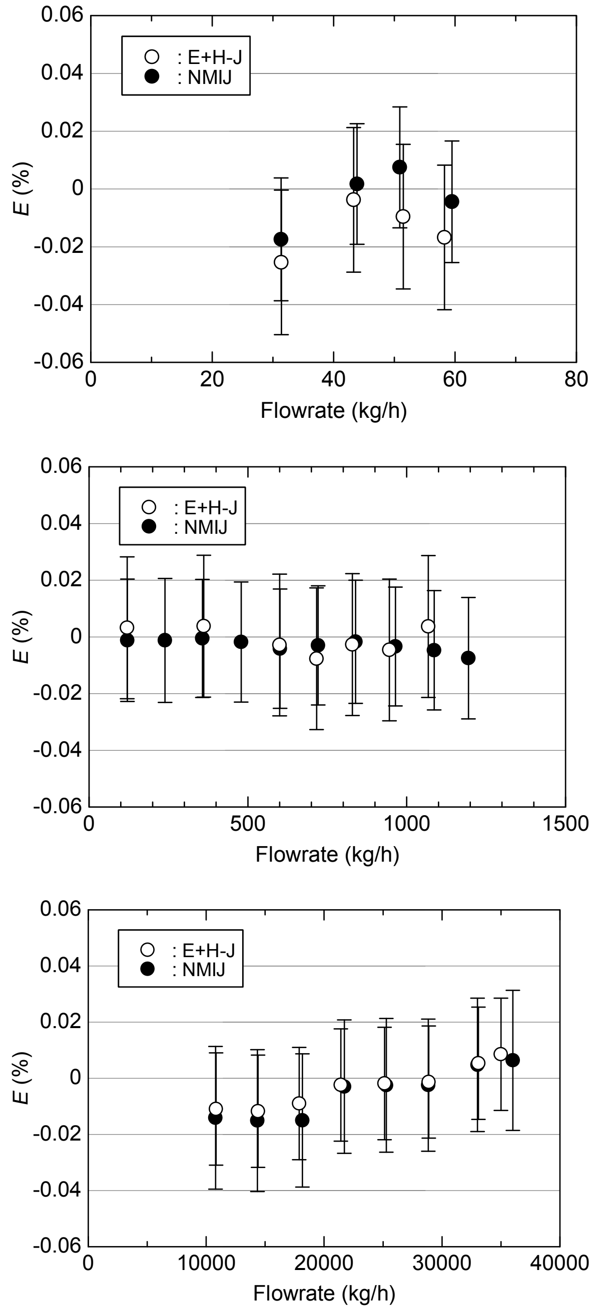

Figure 5: Comparison result

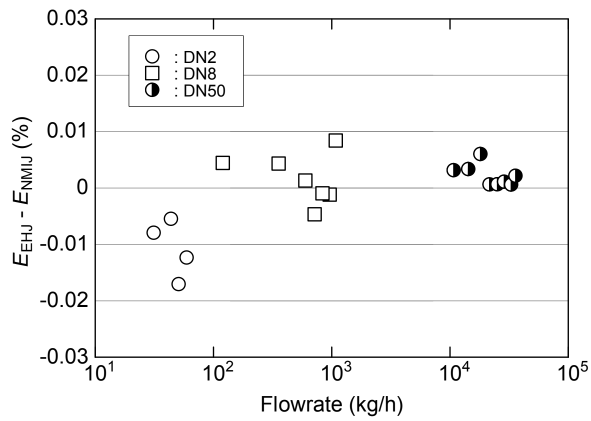

Figure 6: Deviation between two labs.

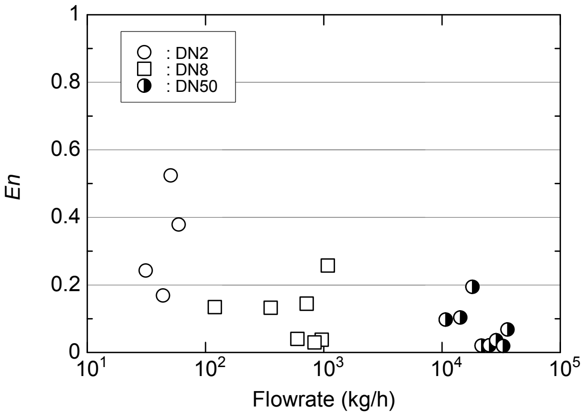

Figure 7: *En* value in comparison

5. Conclusion

In this paper, results of comparison of water flow calibration facilities with extremely low uncertainty at E+H-J and NMIJ are reported. Uncertainty of the mass flowrate was 0.014% to 0.021% (from 0.020% to 0.025% as CMC) at E+H-J and 0.021% to 0.023% at NMIJ. To achieve this low uncertainty, NMIJ carried out a re-evaluation of the uncertainty budget for two weighing tank systems. With advanced control of ambient temperature and calibration, uncertainty level could be reduced to approximately half of that in previous reports.

Comparison between facilities at E+H-J and NMIJ was carried out according to three transfer standards, using a Coriolis flowmeter. The range of flowrate was from 30 kg/h to 36000 kg/h. Comparison results showed excellent agreement for both standards, at less than 0.018%. *En* values are also less than 0.52 for all examined flowrate points. These results demonstrate the consistency of facilities at both labs.

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