The inter-comparison of air speed from 2 m/s to 40 m/s by Pitot static tubes

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Abstract

The Mutual Recognition Arrangement (MRA) is framed by the International Committee of Weights and Measures in order to establish the degree of equivalence of national measurement standards via the key comparisons as well as the inter-comparisons of measurements. Based on this objective, the current work was performed in order to determine the degrees of equivalence among three laboratories in Korea Research Institute of Standards and Science (KRISS), National Metrology Institute of Japan (NMIJ) and HCT company for air speed over the range from 2 m/s to 40 m/s. In this inter-comparison of air speed, two AMCA type Pitot static tubes were considered as artifacts. The reference value (RV) and its uncertainty was calculated from all measurement results reported by the participants. The normalized deviations, E_n-number, were mostly smaller than 1. Consequently, the results of participants were mutually consistent.

1. Introduction

This inter-comparison has been performed between three laboratories including KRISS, NMIJ and HCT in which KRISS played the role of a pilot. Because it takes role of the national metrology laboratory, Gas Flow Standards Group in NMIJ undertakes the function of developing, maintaining and disseminating the national primary standards of gas flow and air speed in Japan. In addition, NMIJ proved their calibration and measurement capabilities of air speed up to 40 m/s by participating in the key comparisons of International Committee for Weights and Measures as well as that of Asia Pacific Metrology Programme as: CCM.FF-K3 [1], [2] and APMP.M.FF-K3 [3]. Similar to the gas flow group in NMIJ, fluid flow group in KRISS is the national laboratory in Republic of Korea. KRISS gives the traceability of liquid flow, gas flow and air speed and performs the research for developing the flow measurement technology. The equivalence of their calibration and measurement capabilities of air speed up to 16 m/s is also published in APMP.M.FF-K3 [3]. HCT is one of the six laboratories accredited by Korea Laboratory Accreditation Scheme (KOLAS) in air speed field and their air speed standard system has the range up to 40 m/s. HCT supplies the calibration and testing services for the industry. The main purpose of this research is to determine the degree of equivalence between three laboratories at the air speed of 2 m/s and 40 m/s. In order to carry out this inter-comparison, three laboratories have calibrated two AMCA type Pitot tubes over the range from 2 m/s to 40 m/s. In advance, the inter-comparison was performed by KRISS and HCT, however, the measuring range of their system is different. The maximum speed of KRISS is 16 m/s and HCT's system is 55 m/s. And NMIJ can measure the air speed up to 90 m/s [4], so NMIJ was invited to ensure this inter-comparison cover the range from 2 m/s to 40 m/s. The arrangement as well as the expression of the inter-comparison result was partly based on the Guidelines of Measurement comparisons in the CIPM MRA [5].

2. Experimental and analysis methods

2.1. Artifacts used in the comparison measurement
There are three types of Pitot static tube recommended in the international standard, ISO 3966 [6] as: AMCA type, NPL type, and CETIAT type. AMCA type is popularly used in the industry. Therefore, in this inter-comparison, two AMCA Pitot tubes were used as the artifacts. The first AMCA Pitot tube (PT1) is produced by United Sensor Company. This has the specifications as the following: the outer diameter d is 2.4 mm, the axis of

stem is $nd = 10d$ from plane of static-pressure holes, and the distance from tip of nose to static-pressure holes is $4d$. The second AMCA Pitot tube (PT2) is manufactured by Airflow Company. Its geometric parameters following: the outer diameter d is equal to 4.7 mm, the axis of stem is $nd = 11d$ from plane of static-pressure holes, and the distance from tip of nose to static-pressure holes is $6.6d$. Meanwhile, these parameters suggested in the international standard are $nd = 16d$ and $8d$, respectively [6]. Two artifacts are illustrated in Figure 1.
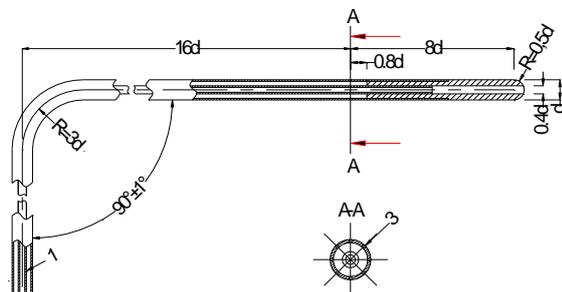
(a)   ISO 3966, specification of AMCA Pitot tube

(b)   PT1   (c)   PT2

Figure 1: AMCA Pitot tubes

In order to measure the dynamic pressure of the artifacts in this research, a Furness micro manometer FCO510 with working ranges of (0-20) Pa and (20-200) Pa for velocity measurements below 20 m/s and an Yokogawa different pressure gauge for velocity measurements above 20 m/s at NMIJ. At KRISS, two precise MKS differential pressure gauges with a working range of (2-200) Pa were used. Meanwhile, at HCT, the same Furness micro manometers FCO510 as at NMIJ was used for velocity measurements below 20 m/s and another Furness micro manometer with working ranges of (0-2000) Pa and (2000-20000) Pa was used for velocity measurements above 20 m/s.

2.2. Medium wind tunnel system in NMIJ
The medium air speed standard system in NMIJ consists of a Gottingen type wind tunnel in which the test section area is 0.4 m × 0.4 m, the working range is from 1.3 m/s to 40 m/s as shown in Figure 3, the maximum turbulent intensity in the test section is 0.03%. The working standard for the wind tunnel is ultrasonic anemometer mounted on the wall of the test section. The anemometer is calibrated by using an LDA system, which has been calibrated against a rotating disc [7]. The expanded uncertainty values of the NMIJ air speed
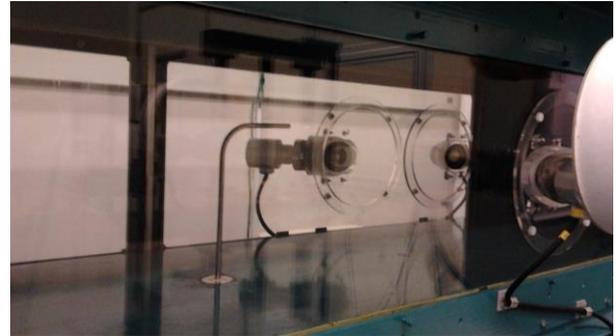

Figure 2: Air speed system in NMIJ

standard system is $[0.297 + 0.27/(v^2 - 0.77v)]$ % from 1.3 m/s to 27.5 m/s and $[-0.0001185v^3 + 0.01157v^2 - 0.3677v + 4.124]$ % from 27.5 m/s to 40 m/s [1].

2.3. Air speed system in KRISS
The air speed standard system in KRISS used for calibrating the two Pitot tubes includes: a subsonic open-circuit wind tunnel in which the test section area is 0.9 m × 0.9 m, the working range is from 2 m/s to 16 m/s as shown Figure 3, and the maximum turbulent intensity in the test section is 0.4%; the reference is a standard NPL Pitot tube and other instruments are two precise MKS differential pressure gauges with a working range of (2-200) Pa for velocity measurements. The expanded uncertainty values of the KRISS standard air speed system is 1.1% from 2 m/s to 5 m/s and 0.6 % from 5 m/s to 16 m/s [8].

Figure 3: Air speed system in KRISS

2.4. Air speed system in HCT
The air speed standard system in HCT consists of a Gottingen wind tunnel having the specifications as the following: the diameter of jet outlet is 255 mm; the length of working section is 320 mm, the working range covers from 0.1 m/s to 55 m/s, and the maximum turbulent intensity in the test section is 0.7%; the reference is an Fp50 LDA system manufactured by ILA company with: beam distance is 45 mm, wavelength is 561 nm. This LDA was calibrated by the National Metrology Institute of Germany (PTB) and its expanded uncertainty is 0.22%. The measurement setup was arranged on the HCT system as shown in Figure 4 and the expanded uncertainty values of the air speed standard system in HCT is 0.44%.
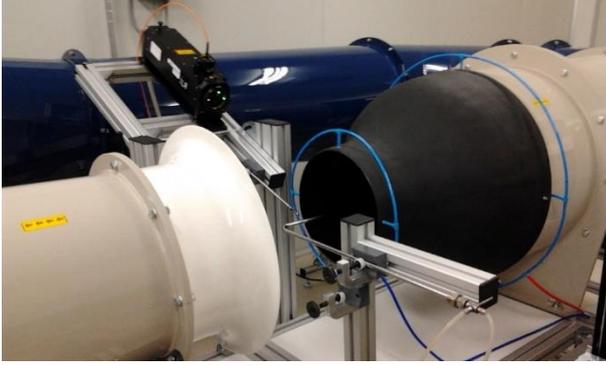
Figure 4: Air speed system in HCT

2.5. Method of measurement and analysis

The calibration of two artifacts was performed by the participants at ambient condition at 10 velocities from 2 m/s to 40 m/s and the two artifacts were completely and separately calibrated. At each velocity, five repeated measurements were recorded in order to calculate the velocity conversion factor K according to the following equation:

$$K = \frac{V_{ref}}{V_{DUT}} \qquad (1)$$

Where, V_{ref} [m/s] is the reference velocity measured by the participant, V_{DUT} [m/s] is the velocity read by the artifacts [2].

Based on the data of K given by the participants, the degree of equivalence of the measurement would be analysed according to the procedure A proposed by Cox [9], [10]. The reference value K_{RV} is considered as a best estimate of the measurand and determined by the weighted mean of the measurements as the equation (2):

$$K_{RV} = \frac{\dfrac{K_{KRISS}}{u^2(K_{KRISS})} + \dfrac{K_{NMIJ}}{u^2(K_{NMIJ})} + \dfrac{K_{HCT}}{u^2(K_{HCT})}}{\dfrac{1}{u^2(K_{KRISS})} + \dfrac{1}{u^2(K_{NMIJ})} + \dfrac{1}{u^2(K_{HCT})}} \qquad (2)$$

where K_{KRISS}, K_{NMIJ} and K_{HCT} are the values of the velocity conversion factor; u_{KRISS}, u_{NMIJ} and u_{HCT} are the standard uncertainty.

And the standard uncertainty of K_{RV} is equal to:

$$u(K_{RV}) = \frac{1}{\dfrac{1}{u^2(K_{KRISS})} + \dfrac{1}{u^2(K_{NMIJ})} + \dfrac{1}{u^2(K_{HCT})}} \qquad (3)$$

Then, all results obtained from participants are tested an overall consistency if a chi-squared test satisfies the equation (4) and (5)

$$\chi^2_{obs} = \frac{(K_{KRISS}-RV)^2}{u^2(K_{KRISS})} + \frac{(K_{NMIJ}-RV)^2}{u^2(K_{NMIJ})} + \frac{(K_{HCT}-RV)^2}{u^2(K_{HCT})} \qquad (4)$$

$$Pr\{\chi^2(v) > \chi^2_{obs}\} > 0.05 \qquad (5)$$

In addition, the degree of equivalence d of each participant displays the deviation from the K_{RV} at each velocity point and it has the expanded uncertainty at 95% level of confidence as the following:

$$d = K - K_{RV} \qquad (6)$$

$$U(d) = 2u(d) \qquad (7)$$

where $u(d)$ is given by $u^2(d) = u^2(K) - u^2(K_{RV})$.

Moreover, the consistency of the participants is indicated by normalized deviations E_n and a value of $|E_n| < 1$ is supposed to show the consistency.

$$E_n = \frac{d}{U(d)} \qquad (8)$$

3. Results and discussions

3.1. Measurement results of PT1

The values of K determined by the participants for PT1 are illustrated in Figure 5 and Figure 6. The results show the consistency between the participants. By using the reciprocals of the squares of the combined standard uncertainties attached to these factors, K_{RV} of the PT1 were determined according to the equation (2). Simultaneously, applying a chi-squared test to do an overall consistency checking of all data. The results obtained were shown in Table 1 and Figure 5. In general, all K measured by participant lie within the uncertainty of the K_{RV} even though, there was a certain scatter of the K values at 2 m/s. This scatter might come from the measurement ability of the differential pressure sensor. But, the normalized deviation values E_n of each participant are all smaller than 1 as shown in Figure 7. This proclaims a consistency between the results of three participants

Table 1: Results of the consistency test for PT1

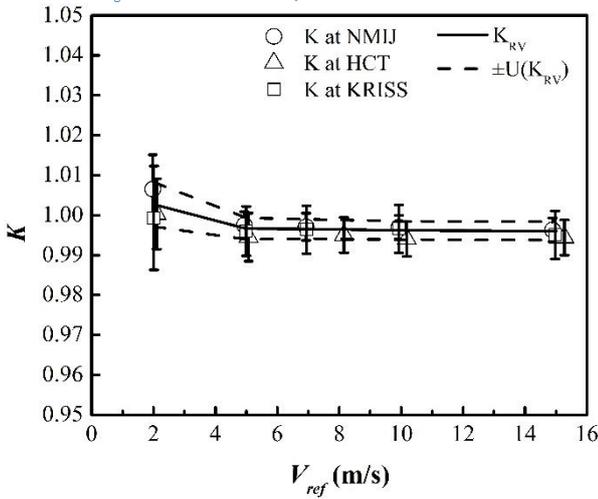| V_{nom} (m/s)	K_{RV}	$U(K_{RV})$	$\chi^2 obs$	n-1	Test $\chi^2 0.05$, $n-1$	Result
2	1.0027	0.0028	1.352	2	5.991	Pass
5	0.9966	0.0013	0.807	2	5.991	Pass
7	0.9965	0.0012	0.811	2	5.991	Pass
10	0.9962	0.0011	1.377	2	5.991	Pass
15	0.9960	0.0011	1.063	2	5.991	Pass
20	0.9987	0.0013	1.815	1	3.841	Pass
25	0.9989	0.0012	0.276	1	3.841	Pass
30	0.9983	0.0013	0.132	1	3.841	Pass
35	0.9972	0.0014	0.206	1	3.841	Pass
40	0.9958	0.0013	0.570	1	3.841	Pass

Figure 5: K for PT1 from 2 m/s to 15 m/s
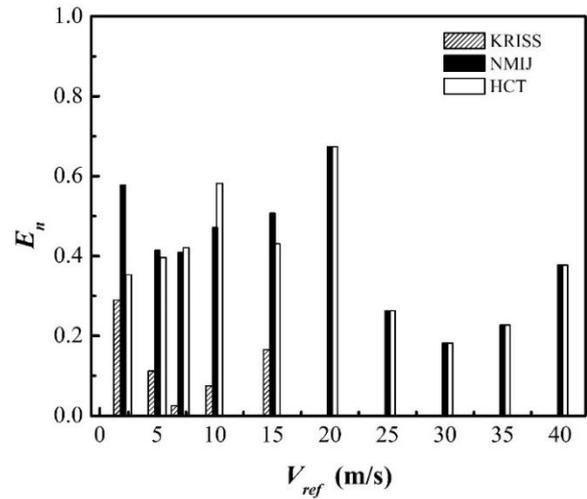

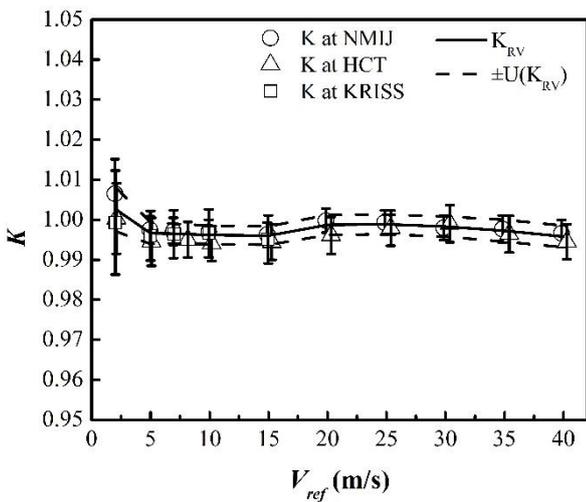
Figure 7: En number for PT1

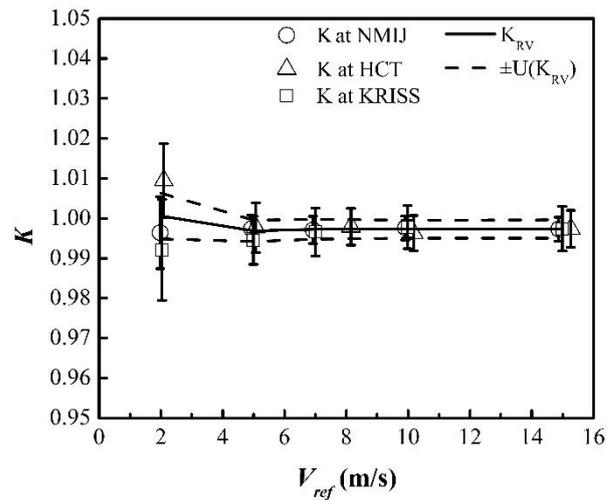**Figure 6:** K for PT1 from 2 m/s to 40 m/s

Figure 8: K for PT2 from 2 m/s to 15 m/s

3.2. Measurement results of PT2

Applying the same calculating procedure for the PT2, the value of K and K_{RV} were followed the equation (1) and (2). The velocity conversion factors were determined by the participants for PT2 summarized on Figure 8 and Figure 9.

At 2 m/s, the calibration result of KRISS and HCT scattered from K_{RV} over its expanded uncertainty. However, at the most of all velocities, the results are on the RV trend and homologous to each other. Consequently, the normalized deviation values En of each participant are mostly smaller than 1 and a high consistency between the results of three participants is shown in Figure 10. The result of an overall consistency check of all data for PT2 was listed in Table 2.

Table 2: Results of the consistency test for PT2

V_{nom} (m/s)	K_{RV}	$U(K_{RV})$	$\chi^2 obs$	n-1	Test $\chi^2 0.05,$ $n-1$	Result
2	1.0006	0.0029	6.435	2	5.991	Pass
5	0.9969	0.0013	0.793	2	5.991	Pass
7	0.9972	0.0012	0.135	2	5.991	Pass
10	0.9973	0.0011	0.281	2	5.991	Pass
15	0.9973	0.0011	0.002	2	5.991	Pass
20	1.0003	0.0013	0.585	1	3.841	Pass
25	1.0001	0.0012	0.317	1	3.841	Pass
30	0.9999	0.0012	0.408	1	3.841	Pass
35	0.9996	0.0013	0.063	1	3.841	Pass
40	0.9981	0.0014	0.020	1	3.841	Pass

In summary, the scattering of K and their uncertainty are getting larger at 2 m/s. To make clear the reason, the Youden graphical diagnose was applied for comparing precision and bias amongst participants [11], [12].
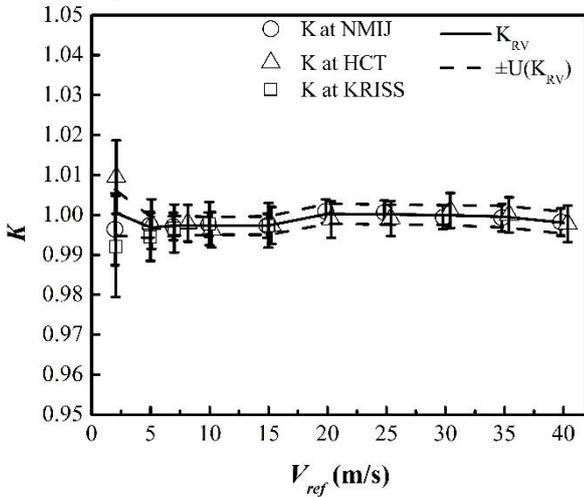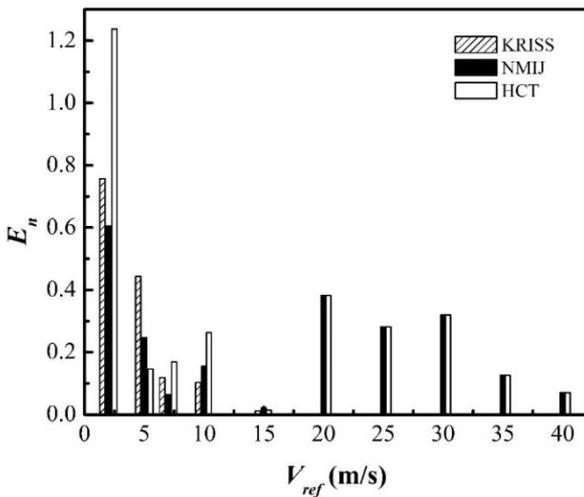
Figure 9: *K* for PT2 from 2 m/s to 40 m/s

Figure 10: *En* number for PT2

Figure 11: Youden plot at 2 m/s

Figure 12: Youden plot at 5 m/s

In the Youden plot, the results of PT1 and PT2 are two axes of graph. The center of Youden circle is the intersection of median lines of PT1 and PT2. The random components are the distances from the each measurement point to the 45 degree line. The radius of this circle is the multiplication of the standard deviation of the random components and 2.45 [11]. Figure 11 & 12 show that all measurement results of participants randomly scattered within the circle. This result implies that there are no systematic errors in this inter-comparison. At the 2 m/s, the big variation of *K* between participants makes random components large so they make the radius of the circle large, as shown in Figure 11. The random effect at 2 m/s possibly comes from the measurement limit of the different pressure gauges and the turbulent intensity in the test section of participants is different. But, at the 5 m/s, all measurement point are close to the circle center and lie almost on the 45 degree line.
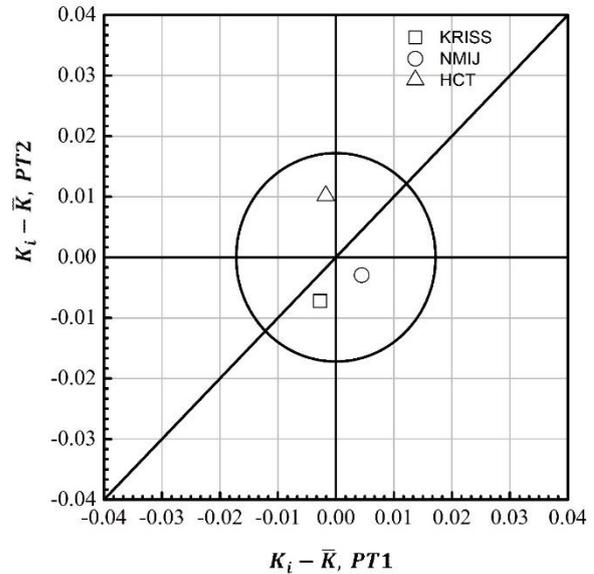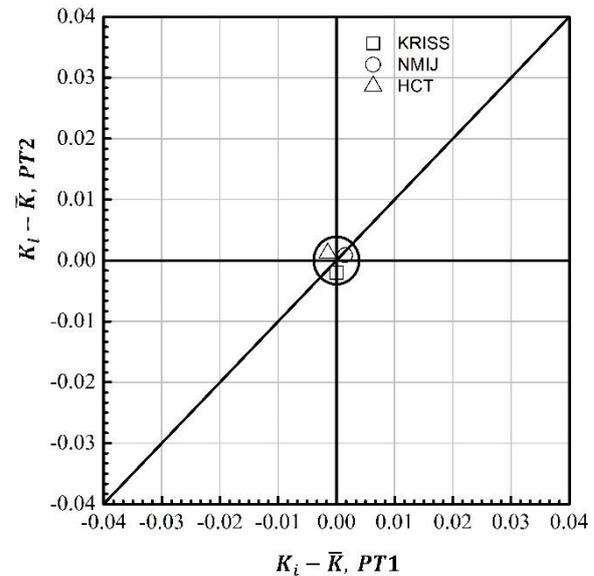
So, the random errors and the radius of circle reduces. It means the random effect at 2 m/s is larger than 5 m/s. This means the all results have high precision and good agreement more than at 2 m/s. Similarly, at the velocity range over than 5 m/s, the measurement data are located within the narrow band of K_{RV} uncertainties. The random effect seems not to have significant contribution to the measurement results.

4. Conclusions

In this inter-comparison, three participants, KRISS, NMIJ and HCT had the experiments at the velocity from

2 m/s to 15 m/s and NMIJ and HCT had the experiments for the velocity above 15 m/s up to 40 m/s. The conclusions drawn from this work are as follows:

1. At the velocity smaller and equal to 2 m/s, the quality of measurement of Piot tubes has quite big influence with the random effect of measurement.
2. Both PT1 and PT2 showed the good performance at the velocity larger than 5 m/s.
3. The calibration results obtained from the participant has a high consistency because the degrees of equivalence and the normalized deviations E_n are mostly smaller than

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