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APMP.M.FF-K3.2020

Air speed measurements

KEY COMPARISON

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Report on the APMP Air Speed Key Comparison (APMP.M.FF-K3.2020)

Final Report
January,2026

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1. Introduction

This key comparison, APMP.M.FF-K3.2020 has been undertaken by APMP/TCFF(Asia Pacific Metrology Programme Technical Committee for Fluid Flow) and was piloted by Center for Measurement Standards, Industrial Technology Research Institute of Taiwan, (CMS,ITRI). An ultrasonic anemometer was used as the transfer standard. The participating NMIs carried out the measurement by using the transfer standard and the pilot lab conducted the data analysis of the measurement results.

The objective of this key comparison is to demonstrate the degree of equivalence of the air speed standards maintained in each participating institute to the CCM.FF-K3.2011 key comparison reference value (KCRV)and to provide supporting evidence for the calibration and measurement capabilities(CMCs) claimed by the participating laboratories in the Asia-Pacific regions.

This report was prepared in accordance with the Guidelines for CIPM Key Comparisons[1] and The Guidelines on conducting comparisons (APMP-G2)[2].

2. Organization

(1) Participants and test speeds

The participating labs and their actual testing dates are listed in Table 1. The comparison was made at the air speeds of (0.5, 2, 5, 10, 15, 20 and 30) m/s. The test air speeds at each participant are also indicated in Table 1.

Seven NMIs participated in air speed comparison. Three NMIs (CMS, NIM and NMIJ) participated in the relevant global key comparison (CCM.FF-K3.2011) [3], ensuring the linkage to the global key comparison in accordance with the APMP guidelines on conducting comparisons (APMP-G2) [2].

Table 1. Participants and test schedule.

#	Participating NMI (Economy)	Contact Person E-mail Address and Phone Number Shipping Address	Test Air Speed (m/s) 0.5	2	5	10	15	20	30
1 Pilot	CMS/ITRI (Taiwan)	JianYuan Chen Jianyuanchen @itri.org.tw, +886-3-5741223 Center for Measurement Standards, Industrial Technology Research Institute 30, Da-Hsueh Rd.,Hsin-Chu city, 300 Taiwan	*	*	*	*	*	*	*
2 Link Lab	NIM (China)	Cui Lishui cuils@nim.ac.cn, +86-10-64525122(6356) National Institute of Metrology of China 18 East Beisanhuan Road,Chaoyang District,Beijing 100013,P.R.China	*	*	*	*	*	*	*
3	NMC, A*STAR (Singapore)	Zeng Yan Zeng Yan@nmc.a-star.edu.sg, +65-6714-9273 #01-20, National Metrology Centre, A*STAR, 8 Cleantech Loop, Singapore 637145	*	*	*	*	*	*	*
4	KRISS (Korea)	Yong Moon Choi ymchoi@kriss.re.kr, +82-42-868-5317 Korea Research Institute of Standards and Science 1 Doryong-Dong, Yuseong-Gu, Daejeon 305-340, Rep.of Korea		*	*	*	*		
5 Link Lab	NMIJ/AIST (Japan)	Noboru Kurihara noboru-kurihara@aist.go.jp, +81-29-861-4376 National Metrology Institute of Japan, National Institute of Advanced Industrial Science and Technology AIST Central 3, 1-1-1 Umezono, Tsukuba, Ibaraki 305-8563, Japan	*	*	*	*	*	*	*
6	NIMT (Thailand)	Padipat Wongthep padipat@mimt.or.th, +66 25775100-2206 National Institute of Metrology, 3/4-5 Moo 3, Klong 5, Klong Luang, Pathumthani 12120 Thailand	*	*	*	*	*	*	*
7	VMI (Vietnam)	Nguyen Duc Tam Tamnd.vmi@gmail.com, +84-915431252 Vietnam Metrology Institute(VMI), N08 Hoang Quoc Viet Road, Cau Giay Dictrict, Hanoi, Vietnam	*	*	*	*	*	*	*

(2) Test schedule

The actual testing dates at each participant are listed in Table 2.

Table 2. Participants and test schedule.

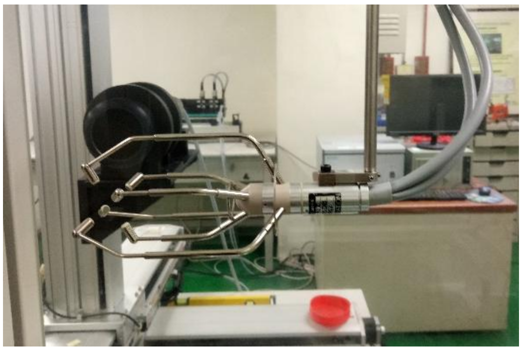
Participating Lab	From	To
CMS (#1)	January 6, 2020	January 17, 2020
NIM	February 17, 2020	March 06, 2020
NMC,A*STAR	March 30, 2020	June 26, 2020
KRISS	July 20, 2020	August 07, 2020
CMS (#2)	September14, 2020	September 25, 2020
NMIJ	October 02, 2020	November 23, 2020
CMS (#3)	December 13, 2020	December 24,2020
NIMT	January 7, 2021	February 24, 2021
CMS (#4)	March 29, 2021	April 16, 2021
VMI	May 20, 2021	July 30, 2021
CMS (#5)	August 9, 2021	August 27, 2021

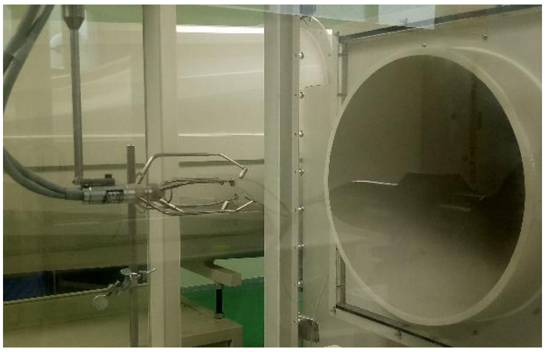
3. Transfer Standard

The ultrasonic anemometer to be used in this key comparison (APMP KC) is manufactured by KAIJO SONIC CORPORAITION. This ultrasonic anemometer is a different model than that is used earlier in CCM.FF-K3.2011.However the performance is similar. The probe has three pairs of ultrasonic transducers to measure the three-dimensional velocity vector derived from the transit time of the ultrasonic waves between each pair of transducers. The projected area of the probe is 1287 mm^2 . The probe was mounted to conduct the measurement in the test section of the wind tunnel in CMS as shown in Fig. 1 (Photo 1 and Photo 2). The signal processing unit provides a scalar value of the air speed, V_m, which is given by

$$V_m = \sqrt{V_x^2 + V_y^2 + V_z^2} \quad (1)$$

where V_x, V_y and V_z denote the components of the three-dimensional velocity vector. This signal processor also gives the time averaged air speed.





(A)Photo 1 (B) Photo 2

Fig. 1 Probe of ultrasonic anemometer mounted for calibration in wind tunnel test section

4. Calibration results

(1) Calibration result

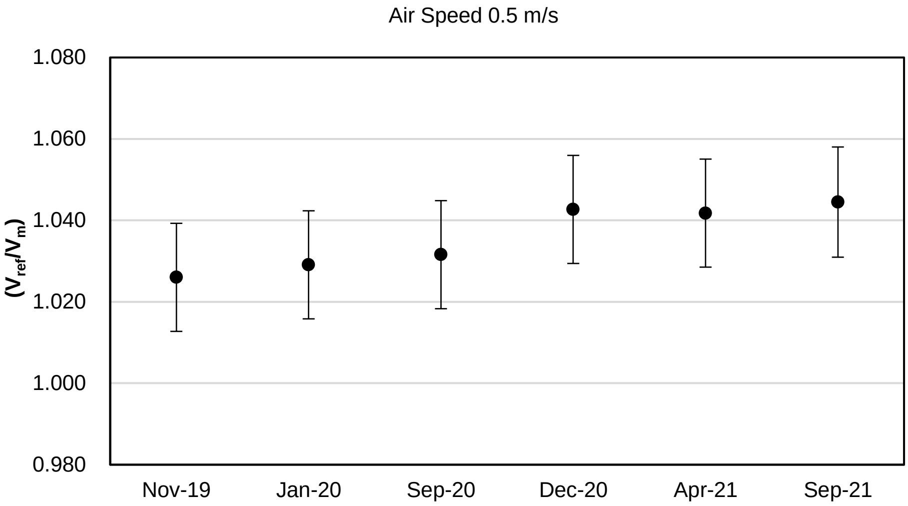
In each participating laboratory, the ratio of the laboratory's reference air speed (V_{ref}) to the time averaged air speed was obtained at each test speed and reported along with their uncertainties. The averaging time was 60 s. In this report the calibration result is represented by

$$x_i , = V_{ref} / \overline{V}_m \qquad (2)$$

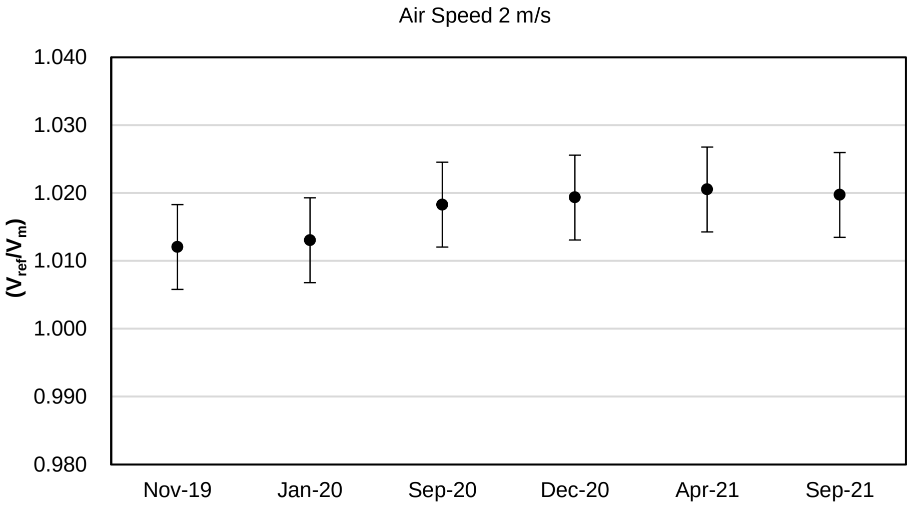
where subscript i denotes the participating lab.

(2) Reproducibility of the transfer standard observed at CMS

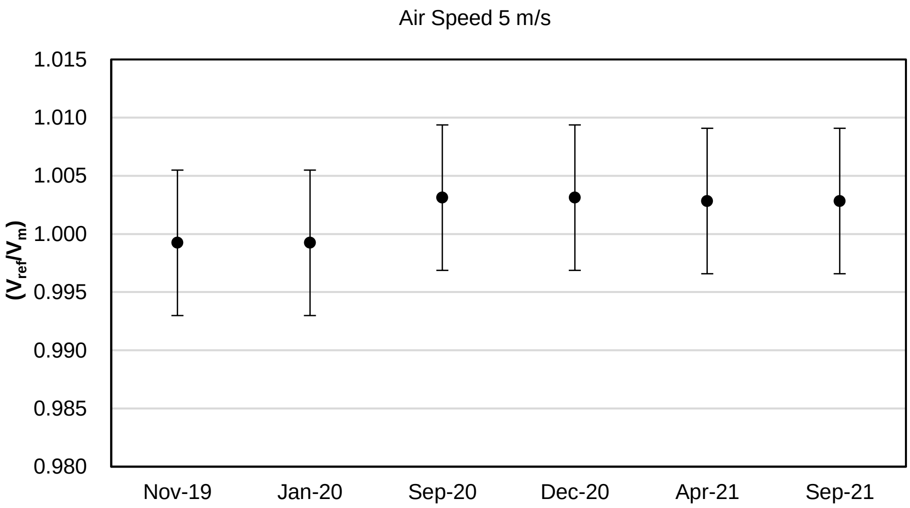
Fig.2 shows the calibration results of the transfer standard in CMS during the comparison. This figure shows that the anemometer was at 0.5 m/s, 2 m/s, 5 m/s, 10 m/s, 15 m/s, 20 m/s and 30 m/s. The drift of the transfer standard was less than 0.30 % in this APMP KC for 10 m/s, 15 m/s, 20 m/s and 30 m/s.



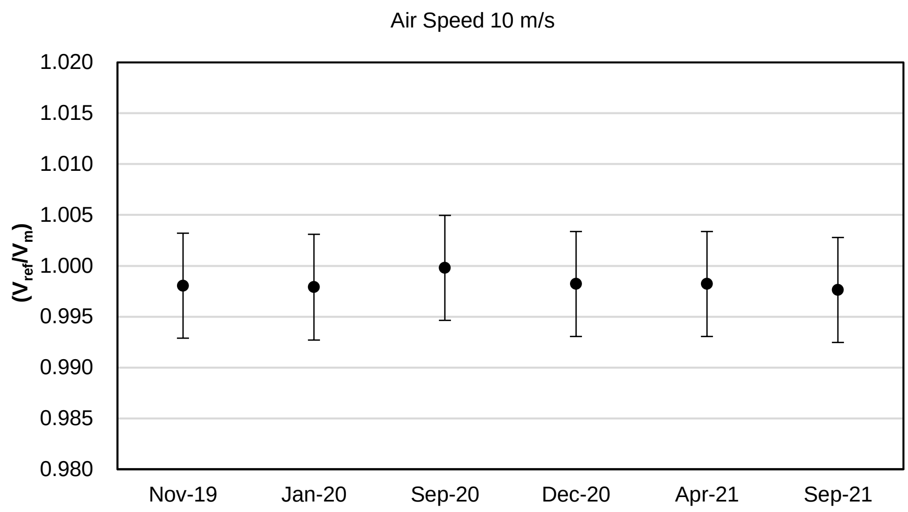
(a) 0.5 m/s



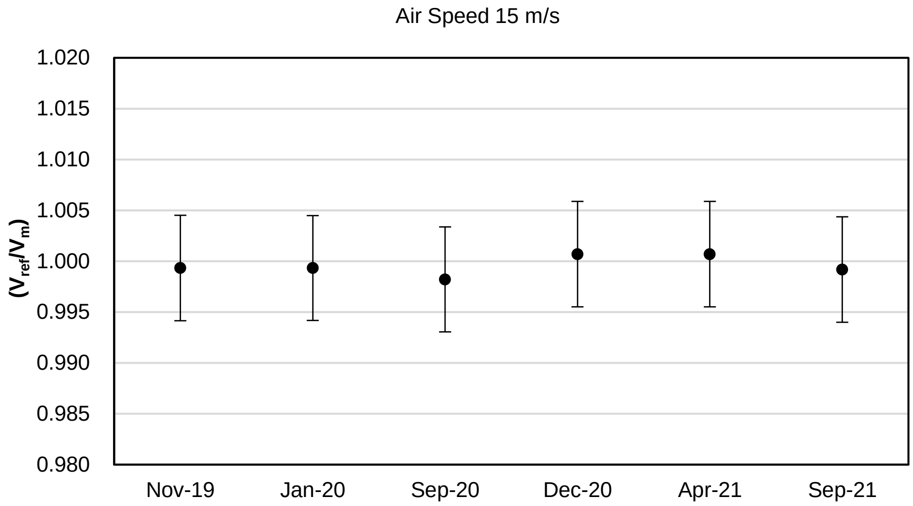
(a) 2 m/s



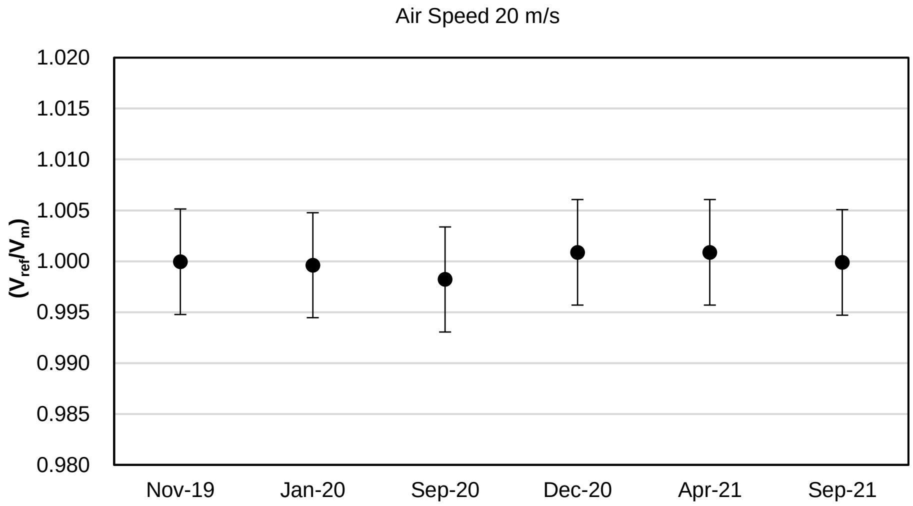
(b) 5 m/s



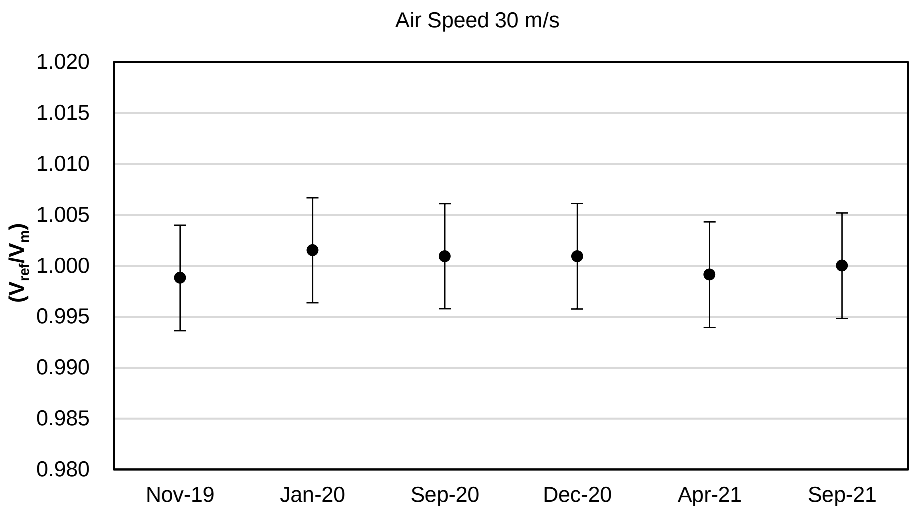
(c) 10 m/s



(d) 15 m/s



(e) 20 m/s



(f) 30 m/s

Fig. 2 Result of reproducibility test of the ultrasonic anemometer

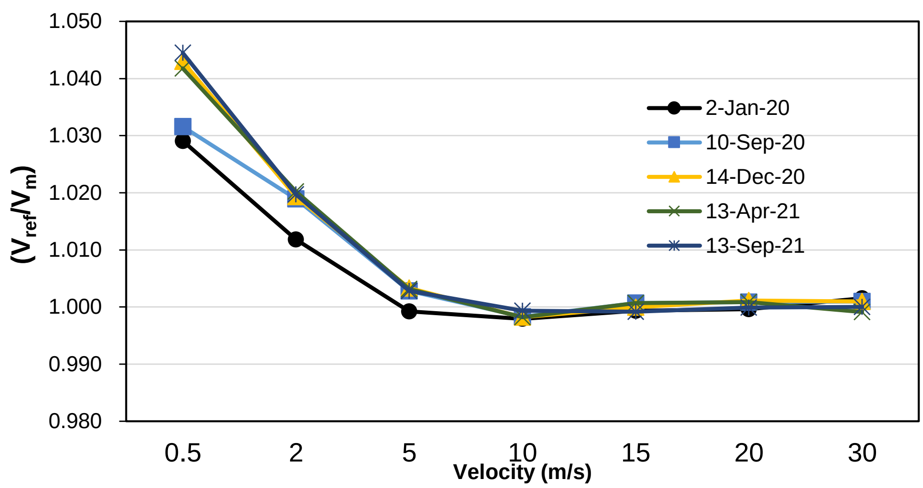


Fig. 3 Reproducibility results of the transfer standard

Five calibrations were performed in CMS between January 2020 and September 2021.The stability of transfer standard is calculated for each velocity as :

$$\frac{Max(x_i)-Min(x_i)}{x_{mean}} \times 100(\%) \tag{3}$$

Where :

x_i is the calibration value obtained by CMS at during the comparison.

x_{mean} is the mean calibration value obtained by CMS considering all the performed calibrations.

The standard uncertainty of the transfer standard at each velocity is calculated by considering a rectangular law, the observed maximum deviation divided by the square root of 12. Table 3 shows the standard uncertainty of the transfer standard based on the results obtained in CMS. An additional uncertainty due to the stability of the transfer standard will be included when calculating the uncertainty of RMO KC.

Table 3 Standard uncertainty of the ultrasonic anemometer

Nominal air speed (m/s)	Standard uncertainty for the transfer standard (%)
0.5	0.45
2	0.25
5	0.12
10	0.04
15	0.04
20	0.08
30	0.07

(3) Calibration results of the participating labs

The calibration results reported from all the participating labs are listed in Table 4. All the reported values are also listed in Appendix B.

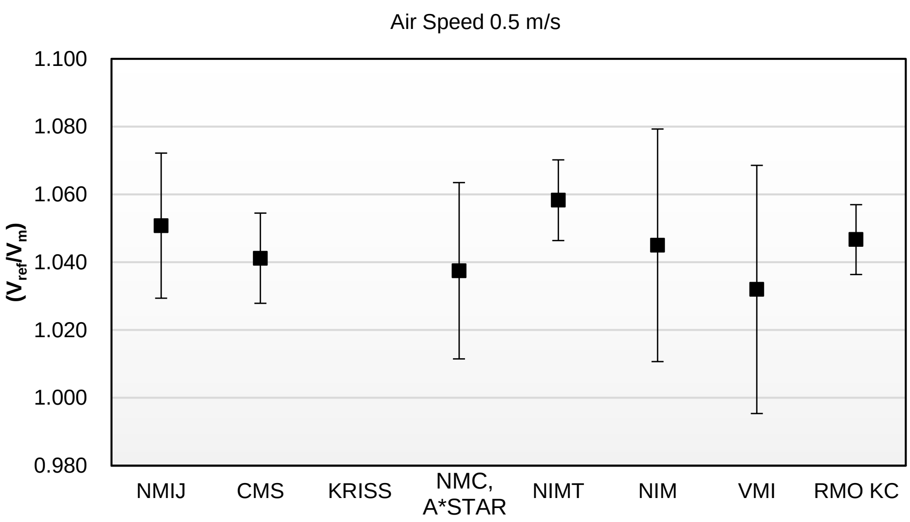
Table 4 Calibration results reported by the participating labs.

$U(x_i)$ is an expanded uncertainty with coverage factor (k) of 2.

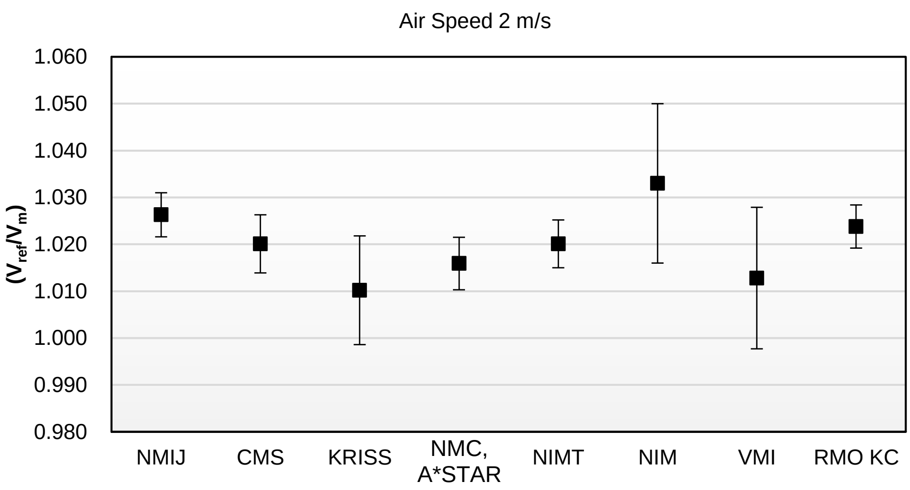
NMI	Air Speed (m/s)							
	0.5		2		5		10	
	Calibration Result x_i	Expanded Uncertainty $U(x_i)$	Calibration Result x_i	Expanded Uncertainty $U(x_i)$	Calibration Result x_i	Expanded Uncertainty $U(x_i)$	Calibration Result x_i	Expanded Uncertainty $U(x_i)$
NMIJ	1.0508	0.0214	1.0263	0.0047	1.0062	0.0036	1.0023	0.0030
CMS	1.0412	0.0133	1.0197	0.0063	1.0028	0.0052	0.9983	0.0052
NIM	1.0453	0.0242	1.0331	0.0119	1.0129	0.0063	0.9989	0.0048
KRISS	-	-	1.0102	0.0116	0.9995	0.0061	1.0001	0.0061
NMC, A*STAR	1.0375	0.026	1.0173	0.0056	1.0086	0.0056	1.0039	0.0056
NIMT	1.0583	0.0119	1.0201	0.0051	1.0047	0.0046	1.0031	0.0046
VMI	1.0320	0.0366	1.0199	0.0152	1.001	0.0085	0.9968	0.0065
RMO KC	1.0471	0.0137	1.0242	0.0068	1.0065	0.0034	0.9989	0.0024

NMI	Air Speed (m/s)					
	15		20		30	
	Calibration Result x_i	Expanded Uncertainty $U(x_i)$	Calibration Result x_i	Expanded Uncertainty $U(x_i)$	Calibration Result x_i	Expanded Uncertainty $U(x_i)$
NMIJ	1.0031	0.0031	1.0035	0.0031	1.0024	0.0031
CMS	0.9992	0.0052	0.9999	0.0052	1.0000	0.0052
NIM	1.0017	0.0047	0.9994	0.0051	0.9984	0.0050
KRISS	1.0008	1.0060	-	-	-	-
NMC, A*STAR	1.0032	0.0048	1.0023	0.0048	0.9968	0.0048
NIMT	1.0043	0.0046	1.0045	0.0045	1.0035	0.0045
RMO KC	1.0005	0.0024	1.0008	0.0027	1.0017	0.0027

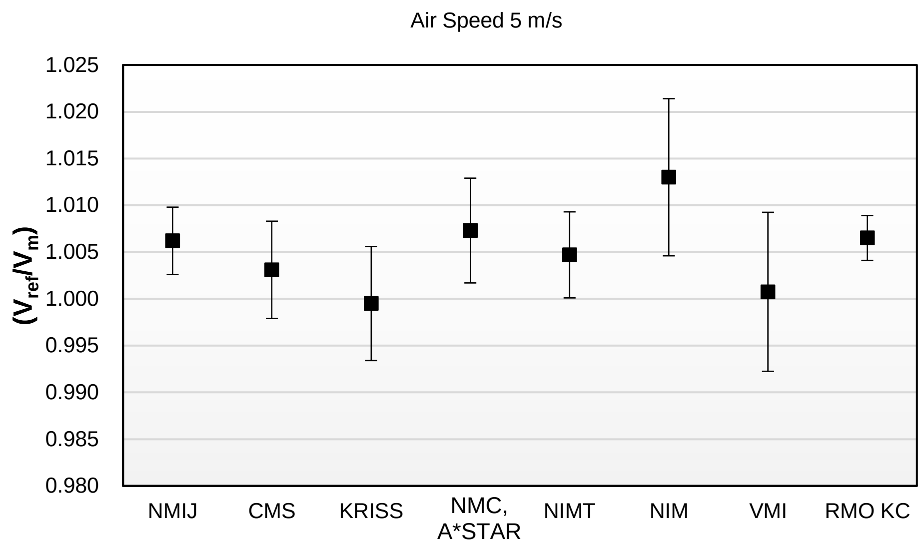
Based on this table, the calibration results at each air speed were compared in Fig. 4. Values of RMO KC are calculated by making corrections to the KCRV values of CCM KC [3] through three APMP link labs. The calculation process will be shown in the next section.



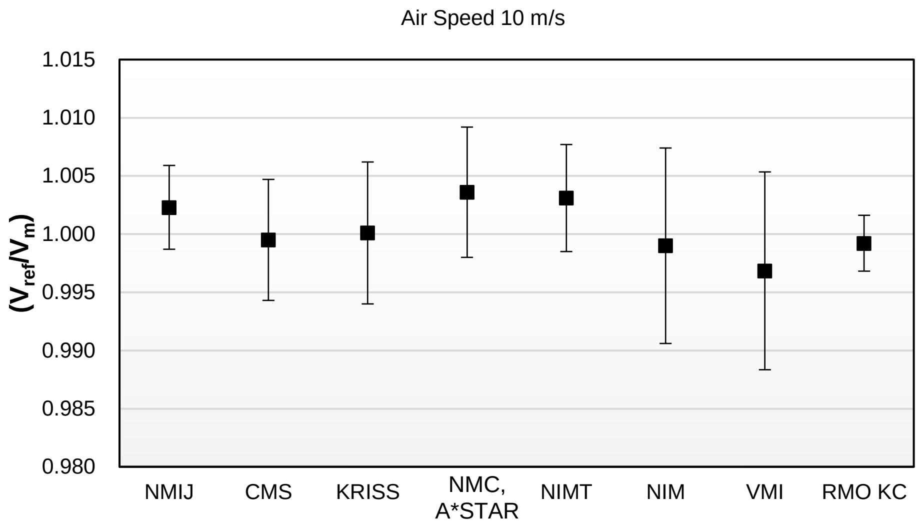
(a) 0.5 m/s



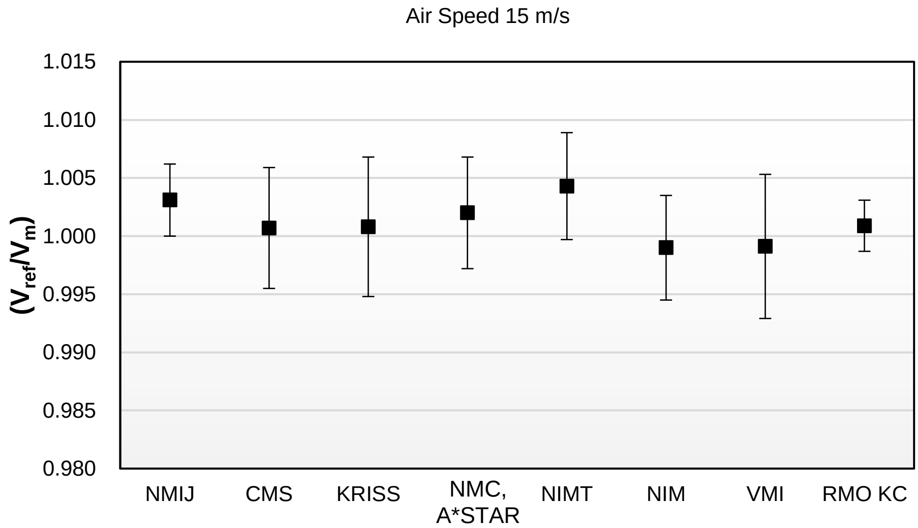
(b) 2 m/s



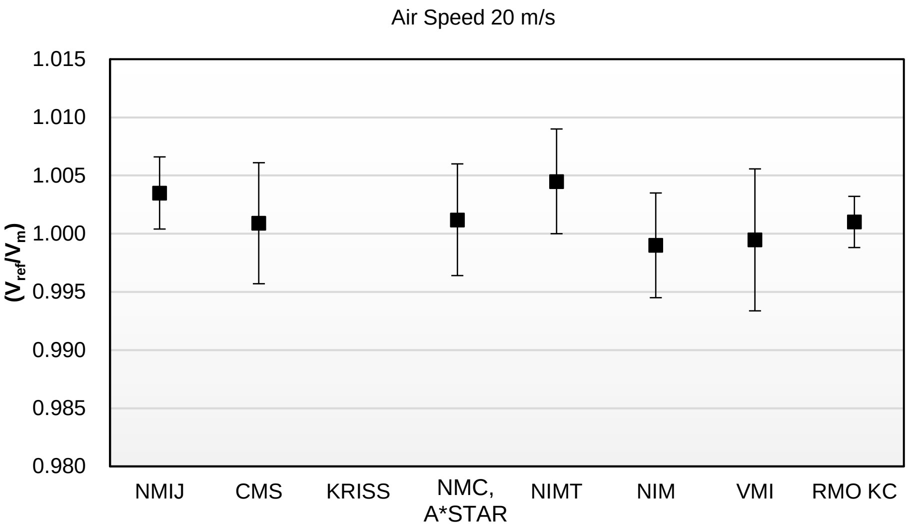
(c) 5 m/s



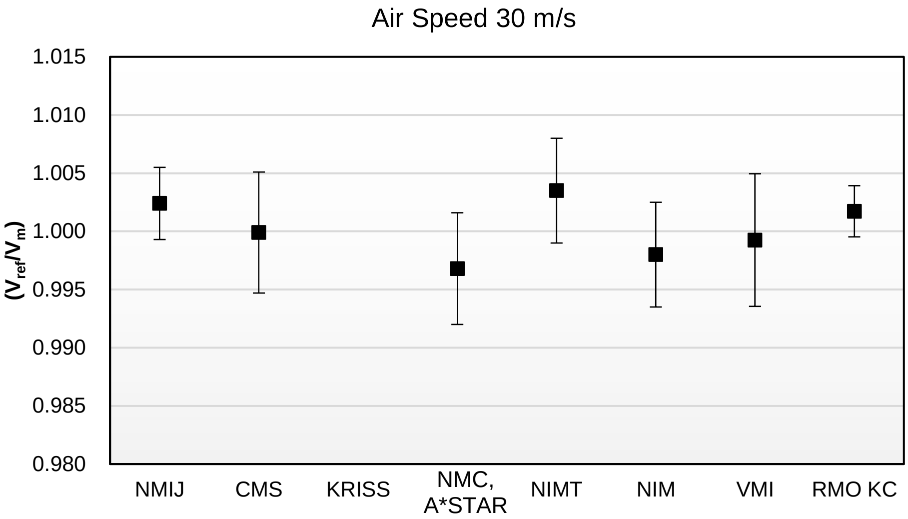
(d) 10 m/s



(e) 15 m/s



(f) 20 m/s



(g) 30 m/s

Fig. 4 Calibration results reported by the participating labs at each air speed

5. Linkage to the global key comparison

The three link laboratories have a result both from CCM.FF-K3.2011 (CCM KC) [3]and APMP.M.FF-K3.2020 (APMP KC). These results are plotted in Fig. 5 in which the key comparison reference value (KCRV), derived from CCM KC, was included. These RMO KC is used as the reference value after the results from APMP KC are corrected by the procedure described by Delahaye and Witt [4].

A correction, which should be applied to the result from APMP KC, was obtained by equation (4):

$$D = \sum w_i \, D_i \tag{4}$$

where D is the difference between the results from CCM KC and APMP KC for the same link laboratory (NMIJ, NIM, CMS) presented by equation (5), and w_i is the weighing coefficient obtained from the uncertainty in APMP KC for each link lab as presented by equation (6).

$$D_i = x_{i,CCM} - x_{i,APMP} \tag{5}$$

$$w_i = \frac{\frac{1}{u_i^2}}{\frac{1}{u_{i,NMIJ}^2} + \frac{1}{u_{i,NIM}^2} + \frac{1}{u_{i,CMS}^2}} \tag{6}$$

With this procedure, the correction was calculated as:

D= -0.0218 at 0.5 m/s,

D= -0.0224 at 2 m/s,

D= -0.0175 at 5 m/s,

D= -0.0118 at 10 m/s,

D= -0.0124 at 15 m/s,

D= -0.0118 at 20 m/s,

D= -0.0139 at 30 m/s,

Finally, corrected value x_i' for each participant of APMP KC was calculated as:

$$x_i' = x_{i,APMP} + D \tag{7}$$

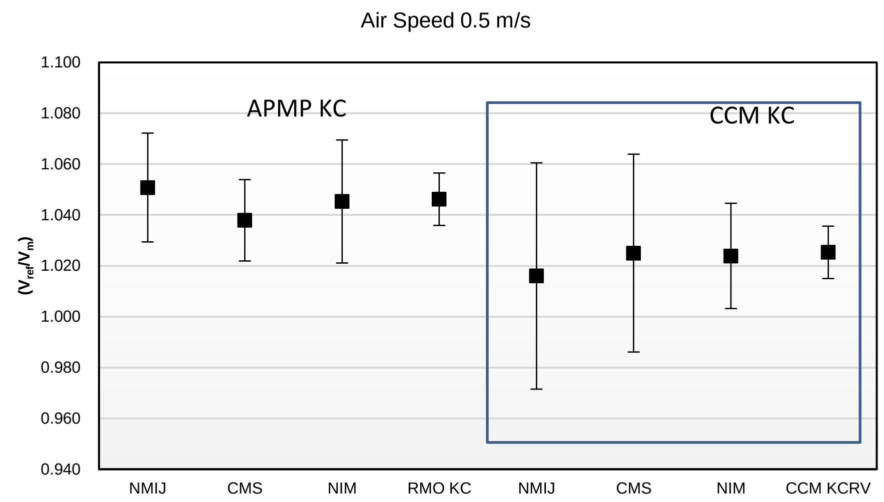
and

$$d_i = x_i' - x_{ref} \tag{8}$$

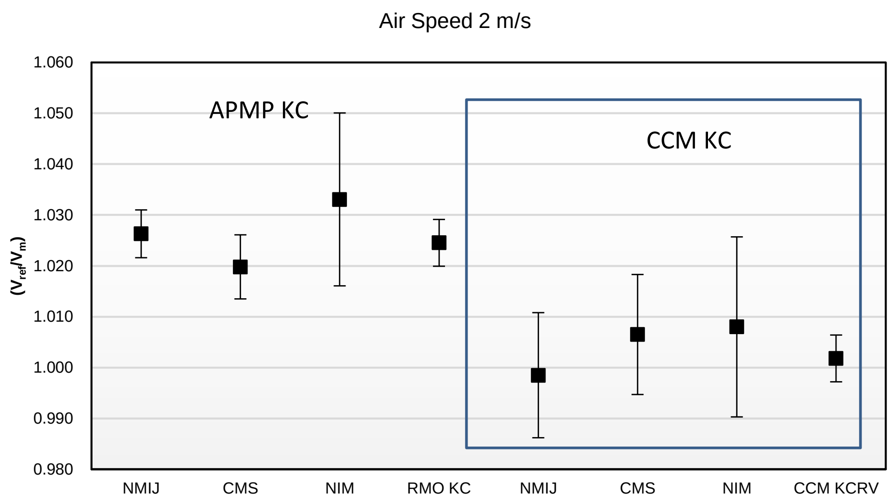
together with equation (7),

$$d_i = x_{i,APMP} - (x_{ref} - D) \tag{9}$$

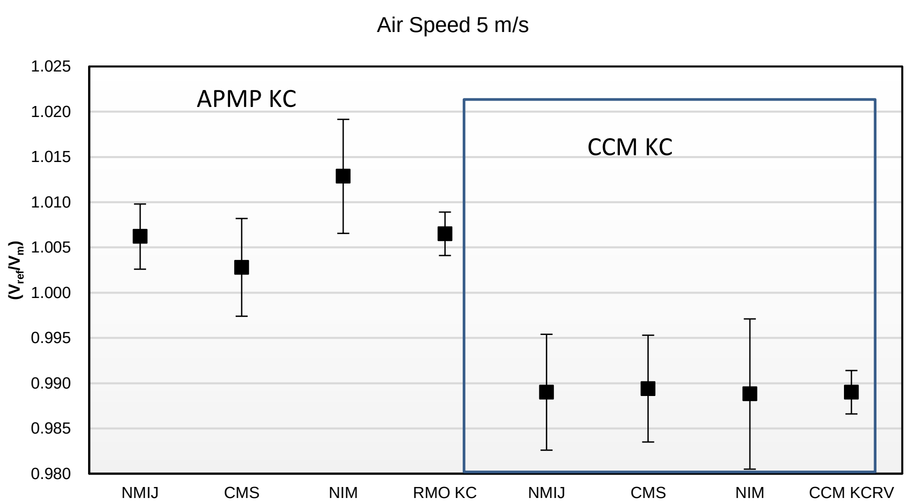
where x_{ref} is the value of KCRV in CCM KC, and $(x_{ref} - D)$ is the value of RMO KC, as shown in Figure 5. Through these three link labs (NMIJ, NIM, and CMS), the results from APMP KC can be linked with KCRV from CCM KC.



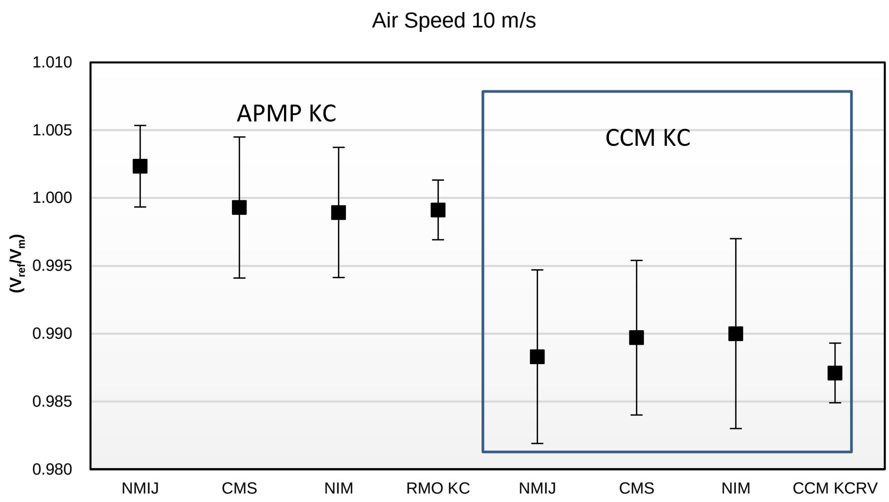
(a) 0.5 m/s



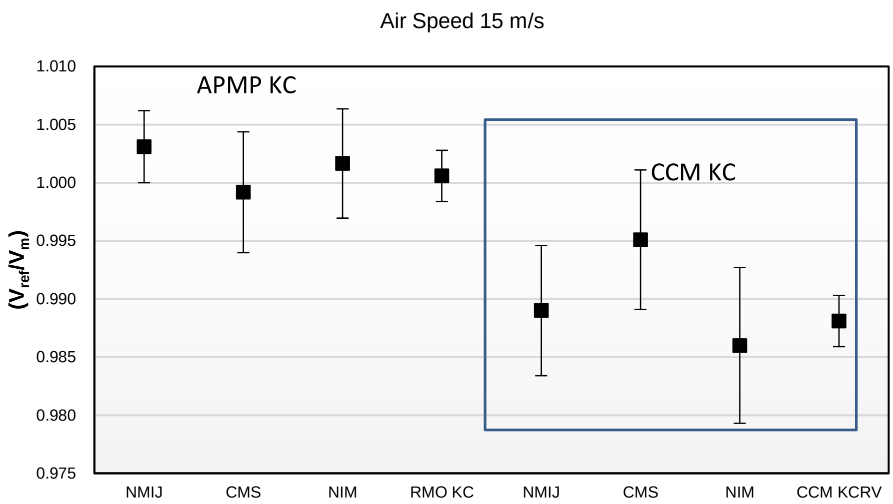
(b) 2 m/s



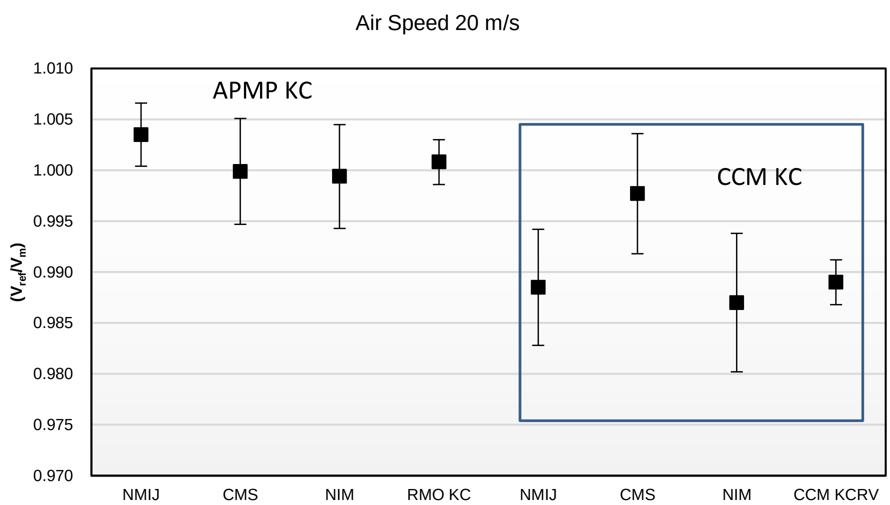
(c) 5 m/s



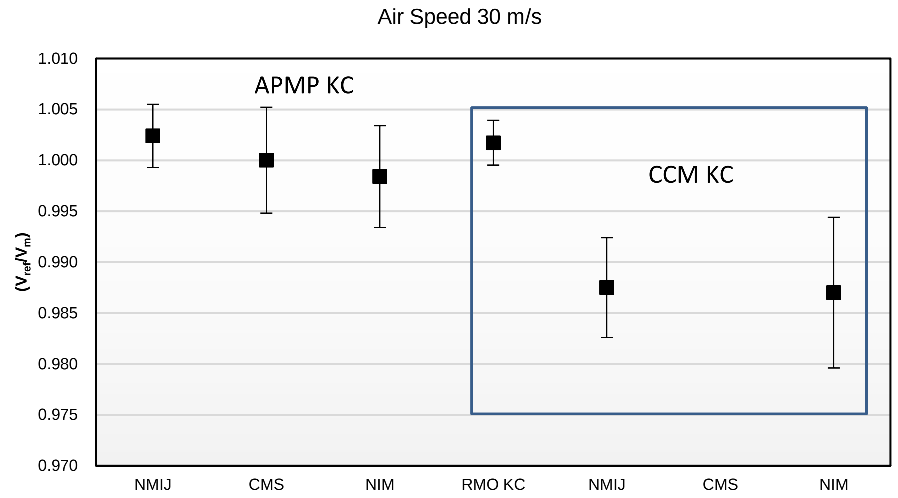
(d) 10 m/s



(e) 15 m/s



(f) 20 m/s



(g) 30 m/s

Fig. 5 Results from the link laboratories at CCM KC and APMP KC

6. Degree of Equivalence

(1) The degree of equivalence for each laboratory with respect to the RMO KC

The expanded uncertainty was obtained using following equations,

$$U(d_i) = 2u(d_i) \tag{10}$$

$$u^2(d_i) = u^2(x_{i,APMP}) + u^2(x_{ref}) + u^2(D) \tag{11}$$

where $u(x_{1,APMP})$, $u(x_{2,APMP})$,.. $u(x_{n,APMP})$ are the standard uncertainties from different laboratories,

$u(x_{ref})$ is the standard uncertainty of the KCRV in CCM KC,

$u(D)$ is the standard uncertainty of the correction D from the three linking laboratories and calculated by

$$\frac{1}{u_D^2} = \frac{1}{u_{D1}^2} + \frac{1}{u_{D2}^2} + \frac{1}{u_{D3}^2} \tag{12}$$

Table 5 Standard uncertainty of the correction *u(D)*

Nominal air speed (m/s)	Standard uncertainty of the correction
0.5	0.0051
2	0.0018
5	0.0013
10	0.0011
15	0.0012
20	0.0012
30	0.0013

The degree of equivalence is defined as APMP En, which was calculated using (13) for each participating laboratory:

$$\mathrm{E_n} = \left| \frac{d_i}{U\,(d_i)} \right| \tag{13}$$

where d_i is calculated by Equation (9) illustrated in the previous section. The APMP E_n is a measure for the equivalence of the results for each laboratory with respect to the RMO KC:

- the results of a laboratory were equivalent (passed) if $E_n \le 1.0$
- the laboratory was determined as not equivalent (failed) if $E_n > 1.2$
- for the value of DoE in the range $1 < E_n \le 1.2$ the "warning level" was defined. In this case some actions to check are recommended to the laboratory

The results of E_n are expressed in Table 6:

Table 6 The degree of equivalence of each participating institute with respect to the RMO KC

Nominal air speed (m/s)	RMO KC	U(RMO KC)	NMIJ			Calibration result V_{ref}/V_m	Expanded Uncertainty $U(V_{ref}/V_m)$
			d_i	$U(d_i)$	E_n		
0.5	1.0471	0.0137	0.0037	0.0274	0.14	1.0508	0.0214
2	1.0242	0.0068	0.0021	0.0090	0.23	1.0263	0.0047
5	1.0065	0.0034	-0.0003	0.0056	0.05	1.0062	0.0036
10	0.9989	0.0024	0.0034	0.0045	0.77	1.0023	0.0031
15	1.0005	0.0024	0.0026	0.0046	0.57	1.0031	0.0031
20	1.0008	0.0027	0.0027	0.0047	0.57	1.0035	0.0031
30	1.0017	0.0027	0.0007	0.0274	0.14	1.0024	0.0031

Nominal air speed (m/s)	RMO KC	U(RMO KC)	CMS			Calibration result V_{ref}/V_m	Expanded Uncertainty $U(V_{ref}/V_m)$
			d_i	$U(d_i)$	E_n		
0.5	1.0471	0.0137	-0.0059	0.0217	0.27	1.0412	0.0133
2	1.0242	0.0068	-0.0045	0.0100	0.45	1.0197	0.0063
5	1.0065	0.0034	-0.0037	0.0068	0.55	1.0028	0.0052
10	0.9989	0.0024	-0.0006	0.0062	0.10	0.9983	0.0052
15	1.0005	0.0024	-0.0013	0.0062	0.21	0.9992	0.0052
20	1.0008	0.0027	-0.0009	0.0063	0.14	0.9999	0.0052
30	1.0017	0.0027	-0.0017	0.0064	0.27	1.0000	0.0052

Nominal air speed (m/s)	RMO KC	U(RMO KC)	NIM			Calibration result V_{ref}/V_m	Expanded Uncertainty $U(V_{ref}/V_m)$
			d_i	$U(d_i)$	E_n		
0.5	1.0471	0.0137	-0.0018	0.0296	0.06	1.0453	0.0242
2	1.0242	0.0068	0.0089	0.0142	0.63	1.0331	0.0119
5	1.0065	0.0034	0.0064	0.0077	0.83	1.0129	0.0063
10	0.9989	0.0024	0.0000	0.0058	0.00	0.9989	0.0048
15	1.0005	0.0024	0.0012	0.0058	0.20	1.0017	0.0047
20	1.0008	0.0027	-0.0014	0.0062	0.23	0.9994	0.0051
30	1.0017	0.0027	-0.0033	0.0063	0.53	0.9984	0.0050

Nominal air speed (m/s)	RMO KC	U(RMO KC)	NMC,A*STAR			Calibration result V_{ref}/V_m	Expanded Uncertainty $U(V_{ref}/V_m)$
			d_i	$U(d_i)$	E_n		
0.5	1.0471	0.0137	-0.0096	0.0311	0.31	1.0375	0.0260
2	1.0242	0.0068	-0.0069	0.0095	0.72	1.0173	0.0056
5	1.0065	0.0034	0.0021	0.0071	0.29	1.0086	0.0056
10	0.9989	0.0024	0.0050	0.0065	0.76	1.0039	0.0056
15	1.0005	0.0024	0.0027	0.0058	0.47	1.0032	0.0048
20	1.0008	0.0027	0.0015	0.0060	0.24	1.0023	0.0048
30	1.0017	0.0027	-0.0049	0.0061	0.80	0.9968	0.0048

Nominal air speed (m/s)	RMO KC	U(RMO KC)	KRISS			Calibration result V_{ref}/V_m	Expanded Uncertainty $U(V_{ref}/V_m)$
			d_i	$U(d_i)$	E_n		
2	1.0242	0.0068	-0.0140	0.0151	0.93	1.0102	0.0130
5	1.0065	0.0034	-0.0070	0.0085	0.83	0.9995	0.0073
10	0.9989	0.0024	0.0012	0.0069	0.17	1.0001	0.0061
15	1.0005	0.0024	0.0003	0.0069	0.04	1.0008	0.0060

Nominal air speed (m/s)	RMO KC	U(RMO KC)	NIMT			Calibration result V_{ref}/V_m	Expanded Uncertainty $U(V_{ref}/V_m)$
			d_i	$U(d_i)$	E_n		
0.5	1.0471	0.0137	0.0112	0.0209	0.54	1.0583	0.0119
2	1.0242	0.0068	-0.0041	0.0093	0.45	1.0201	0.0051
5	1.0065	0.0034	-0.0018	0.0063	0.29	1.0047	0.0046
10	0.9989	0.0024	0.0042	0.0056	0.74	1.0031	0.0046
15	1.0005	0.0024	0.0038	0.0057	0.67	1.0043	0.0046
20	1.0008	0.0027	0.0037	0.0058	0.65	1.0045	0.0045
30	1.0017	0.0027	0.0018	0.0059	0.29	1.0035	0.0045

Nominal air speed (m/s)	RMO KC	U(RMO KC)	VMI			Calibration result V_{ref}/V_m	Expanded Uncertainty $U(V_{ref}/V_m)$
			d_i	$U(d_i)$	E_n		
0.5	1.0471	0.0137	-0.0151	0.0404	0.37	1.0320	0.0366
2	1.0242	0.0068	-0.0043	0.0170	0.25	1.0199	0.0152
5	1.0065	0.0034	-0.0057	0.0095	0.60	1.0008	0.0085
10	0.9989	0.0024	-0.0021	0.0073	0.28	0.9968	0.0065
15	1.0005	0.0024	-0.0014	0.0070	0.20	0.9991	0.0062
20	1.0008	0.0027	-0.0013	0.0071	0.19	0.9995	0.0061
30	1.0017	0.0027	-0.0024	0.0068	0.36	0.9993	0.0057

(2) Degree of Equivalence between participants

$$d_{i,j} = x_{i,} - x_j \quad \text{at other air speeds} \qquad (14)$$

$$U(d_{i,j}) = 2u(d_{i,j}) \qquad (15)$$

$$u^2(d_{i,j}) = u^2(x_i) + u^2(x_j) \qquad (16)$$

The results are listed in Table 7 to Table 13.

Table 7 Degree of equivalence between participants and its expanded uncertainty at 0.5 m/s

	NMIJ		CMS		NIM		NMC, A*STAR		NNIIT		VMI	
	$d_{i,j}$	$U(d_{i,j})$	$d_{i,j}$	$U(d_{i,j})$	$d_{i,j}$	$U(d_{i,j})$	$d_{i,j}$	$U(d_{i,j})$	$d_{i,j}$	$U(d_{i,j})$	$d_{i,j}$	$U(d_{i,j})$
NMIJ	-	-	-0.0096	0.0252	-0.0055	0.0323	-0.0133	0.0337	0.0075	0.0245	-0.0188	0.0424
CMS	0.0096	0.0252	-	-	0.0041	0.0276	-0.0037	0.0292	0.0171	0.0179	-0.0092	0.0389
NIM	0.0055	0.0323	-0.0041	0.0276	-	-	-0.0078	0.0355	0.0130	0.0270	-0.0133	0.0439
MNC A*STAR	0.0133	0.0337	0.0037	0.0292	0.0078	0.0355	-	-	0.0208	0.0286	-0.0055	0.0449
NIMT	-0.0075	0.0245	0.0014	0.0137	-0.0130	0.0270	-0.0208	0.0286	-	-	-0.0263	0.0385
VMI	0.0188	0.0424	0.0092	0.0389	0.0133	0.0439	0.0386	0.0264	0.0263	0.0385	-	-

Table 8 Degree of equivalence between participants and its expanded uncertainty at 2 m/s

	NMIJ		CMS		NIM		NMC, A*STAR		KRISS		NNIIT		VMI	
	$d_{i,j}$	$U(d_{i,j})$	$d_{i,j}$	$U(d_{i,j})$	$d_{i,j}$	$U(d_{i,j})$	$d_{i,j}$	$U(d_{i,j})$	$d_{i,j}$	$U(d_{i,j})$	$d_{i,j}$	$U(d_{i,j})$	$d_{i,j}$	$U(d_{i,j})$
NMIJ	-	-	-0.0066	0.0079	0.0068	0.0128	-0.0090	0.0073	-0.0161	0.0138	-0.0062	0.0070	-0.0064	0.0159
CMS	0.0066	0.0079	-	-	0.0134	0.0135	-0.0024	0.0084	-0.0095	0.0144	0.0004	0.0081	0.0002	0.0165
NIM	-0.0068	0.0128	-0.0134	0.0135	-	-	-0.0158	0.0132	-0.0229	0.0176	-0.0130	0.0130	-0.0132	0.0193
NMC, A*STAR	0.0090	0.0073	0.0024	0.0084	0.0158	0.0132	-	-	-0.0071	0.0142	0.0027	0.0076	0.0026	0.0162
KRISS	0.0161	0.0138	0.0095	0.0144	0.0229	0.0176	0.0071	0.0142	-	-	0.0099	0.0140	0.0097	0.0200
NIMT	0.0062	0.0070	-0.0004	0.0081	0.0130	0.0130	-0.0027	0.0076	-0.0099	0.0140	-	-	-0.0002	0.0160
VMI	0.0064	0.0159	-0.0002	0.0165	0.0132	0.0193	-0.0026	0.0162	-0.0097	0.0200	0.0002	0.0160	-	-

Table 9 Degree of equivalence between participants and its expanded uncertainty at 5 m/s

	NMIJ		CMS		NIM		NMC, A*STAR		KRISS		NNIIT		VMI	
	$d_{i,j}$	$U(d_{i,j})$	$d_{i,j}$	$U(d_{i,j})$	$d_{i,j}$	$U(d_{i,j})$	$d_{i,j}$	$U(d_{i,j})$	$d_{i,j}$	$U(d_{i,j})$	$d_{i,j}$	$U(d_{i,j})$	$d_{i,j}$	$U(d_{i,j})$
NMIJ	-	-	-0.0034	0.0063	0.0067	0.0073	0.0024	0.0067	-0.0067	0.0081	-0.0015	0.0058	-0.0054	0.0092
CMS	0.0034	0.0063	-	-	0.0101	0.0082	0.0058	0.0076	-0.0033	0.0090	0.0019	0.0069	-0.0020	0.0100
NIM	-0.0067	0.0073	-0.0101	0.0082	-	-	-0.0043	0.0084	-0.0134	0.0096	-0.0082	0.0078	-0.0121	0.0106
NMC A*STAR	-0.0024	0.0067	-0.0058	0.0076	0.0043	0.0084	-	-	-0.0091	0.0092	-0.0039	0.0072	-0.0078	0.0102
KRISS	0.0067	0.0081	0.0033	0.0090	0.0134	0.0096	0.0091	0.0092	-	-	0.0052	0.0129	0.0013	0.0112
NIMT	0.0015	0.0058	-0.0019	0.0069	0.0082	0.0078	0.0039	0.0072	-0.0052	0.0086	-	-	-0.0039	0.0097
VMI	0.0054	0.0092	0.0020	0.0100	0.0121	0.0106	0.0078	0.0102	-0.0013	0.0112	0.0039	0.0131	-	-

Table 10 Degree of equivalence between participants and its expanded uncertainty at 10 m/s

	NMIJ		CMS		NIM		NMC, A*STAR		KRISS		NNIIT		VMI	
	$d_{i,j}$	$U(d_{i,j})$	$d_{i,j}$	$U(d_{i,j})$	$d_{i,j}$	$U(d_{i,j})$	$d_{i,j}$	$U(d_{i,j})$	$d_{i,j}$	$U(d_{i,j})$	$d_{i,j}$	$U(d_{i,j})$	$d_{i,j}$	$U(d_{i,j})$
NMIJ	-	-	-0.0040	0.0060	-0.0034	0.0057	0.0015	0.0064	-0.0023	0.0068	0.0007	0.0055	-0.0055	0.0072
CMS	0.0040	0.0060	-	-	0.0006	0.0071	0.0056	0.0076	0.0018	0.0080	0.0048	0.0069	-0.0015	0.0083
NIM	0.0034	0.0057	-0.0006	0.0071	-	-	0.0049	0.0074	0.0011	0.0078	0.0042	0.0066	-0.0021	0.0081
NMC, A*STAR	-0.0015	0.0064	-0.0056	0.0076	-0.0049	0.0074	-	-	-0.0038	0.0083	-0.0008	0.0072	-0.0070	0.0086
KRISS	0.0023	0.0068	-0.0018	0.0080	-0.0011	0.0078	0.0038	0.0083	-	-	0.0030	0.0076	-0.0032	0.0089
NIMT	-0.0007	0.0055	-0.0048	0.0069	-0.0042	0.0066	0.0008	0.0072	-0.0030	0.0076	-	-	-0.0062	0.0079
VMI	0.0055	0.0072	0.0015	0.0083	0.0021	0.0081	0.0070	0.0086	0.0032	0.0089	0.0062	0.0079	-	-

Table 11 Degree of equivalence between participants and its expanded uncertainty at 15 m/s

	NMIJ		CMS		NIM		NMC, A*STAR		KRISS		NNIIT		VMI	
	$d_{i,j}$	$U(d_{i,j})$	$d_{i,j}$	$U(d_{i,j})$	$d_{i,j}$	$U(d_{i,j})$	$d_{i,j}$	$U(d_{i,j})$	$d_{i,j}$	$U(d_{i,j})$	$d_{i,j}$	$U(d_{i,j})$	$d_{i,j}$	$U(d_{i,j})$
NMIJ	-	-	-0.0039	0.0061	-0.0014	0.0056	0.0001	0.0057	-0.0030	0.0068	0.0012	0.0055	-0.0040	0.0069
CMS	0.0039	0.0061	-	-	0.0025	0.0070	0.0040	0.0071	0.0009	0.0080	0.0051	0.0069	-0.0001	0.0081
NIM	0.0014	0.0056	-0.0025	0.0070	-	-	0.0016	0.0067	-0.0016	0.0077	0.0026	0.0066	-0.0025	0.0078
NMC, A*STAR	-0.0001	0.0057	-0.0040	0.0071	-0.0016	0.0067	-	-	-0.0031	0.0078	0.0011	0.0067	-0.0041	0.0078
KRISS	0.0023	0.0068	-0.0016	0.0079	0.0009	0.0076	0.0024	0.0077	-	-	0.0035	0.0076	-0.0017	0.0086
NIMT	-0.0012	0.0055	-0.0051	0.0069	-0.0026	0.0066	-0.0011	0.0067	-0.0042	0.0076	-	-	-0.0052	0.0077
VMI	0.0040	0.0069	0.0001	0.0081	0.0025	0.0078	0.0041	0.0078	0.0010	0.0087	0.0052	0.0077	-	-

Table 12 Degree of equivalence between participants and its expanded uncertainty at 20 m/s

	NMIJ		CMS		NIM		NMC, A*STAR		NNIIT		VMI	
	$d_{i,j}$	$U(d_{i,j})$	$d_{i,j}$	$U(d_{i,j})$	$d_{i,j}$	$U(d_{i,j})$	$d_{i,j}$	$U(d_{i,j})$	$d_{i,j}$	$U(d_{i,j})$	$d_{i,j}$	$U(d_{i,j})$
NMIJ	-	-	-0.0036	0.0061	-0.0041	0.0060	-0.0003	0.0057	0.0010	0.0055	-0.0040	0.0068
CMS	0.0036	0.0061	-	-	-0.0005	0.0073	0.0033	0.0071	0.0033	0.0071	-0.0004	0.0080
NIM	0.0041	0.0060	0.0005	0.0073	-	-	0.0038	0.0070	0.0052	0.0068	0.0001	0.0080
NMC, A*STAR	0.0012	0.0057	-0.0024	0.0071	-0.0029	0.0070	-	-	0.0023	0.0066	-0.0028	0.0078
NIMT	-0.0010	0.0031	-0.0047	0.0069	-0.0052	0.0079	-0.0013	0.0066	-	-	-0.0051	0.0076
VMI	0.0040	0.0068	0.0004	0.0080	-0.0001	0.0080	0.0038	0.0078	0.0051	0.0076	-	-

Table 13 Degree of equivalence between participants and its expanded uncertainty at 30 m/s

	NMIJ		CMS		NIM		NMC, A*STAR		NNIIT		VMI	
	$d_{i,j}$	$U(d_{i,j})$	$d_{i,j}$	$U(d_{i,j})$	$d_{i,j}$	$U(d_{i,j})$	$d_{i,j}$	$U(d_{i,j})$	$d_{i,j}$	$U(d_{i,j})$	$d_{i,j}$	$U(d_{i,j})$
NMIJ	-	-	-0.0024	0.0061	-0.0040	0.0059	-0.0056	0.0057	0.0011	0.0055	-0.0031	0.0065
CMS	0.0024	0.0061	-	-	-0.0059	0.0068	-0.0075	0.0067	-0.0008	0.0065	-0.0008	0.0077
NIM	0.0040	0.0059	0.0016	0.0072	-	-	-0.0016	0.0069	0.0051	0.0068	0.0009	0.0076
NMC A*STAR	0.0056	0.0057	0.0032	0.0071	0.0016	0.0069	-	-	0.0066	0.0066	0.0024	0.0075
NIMT	0.0016	0.0068	-0.0035	0.0069	-0.0051	0.0068	-0.0066	0.0066	-	-	-0.0042	0.0073
VMI	0.0031	0.0065	0.0008	0.0077	-0.0009	0.0076	-0.0024	0.0075	0.0042	0.0073	-	-

7. Summary and conclusion

The seven participating labs participated in the key comparison for air speed measurement from 2020 to 2021. The same ultrasonic anemometer which was used in the first run in 2009 was used again in this run as the transfer standard. The performance of the transfer standard and its reproducibility were evaluated based on the measurement data provided by the pilot lab CMS. The transfer standard showed good stability since the uncertainty caused by the transfer standard was less than the quoted uncertainties of the participants. The KCRV with the correction was defined as RMO KC and the calculated degree of equivalence for each lab with respect to the RMO KC are less than 1 as shown in Table 4 and Table 6,demonstrating the consistency of the measurement results among different labs.

Firstly, the pilot would like to express the deepest appreciation to the National Metrology Institute of Japan (NMIJ) to provide the ultrasonic anemometer as the transfer standard for all the participants to carry out this comparison. Secondly, we would like to thank National Institute of Metrology China (NIM) for their assistance in the custom clearance. Moreover, we would like to thank NMC, A*STAR and KRISS for their comments to improve the report.

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Appendix- Uncertainty budget of participating laboratories

In this appendix, the uncertainty budget of each participating laboratory is presented. Each part is take from the document submitted by the participants and has not been edited by the pilot lab.

A.1. CMS

Air Speed Calibration System

The air speed calibration system at CMS consists of the wind tunnel and transfer standard LDV as shown in figure 1.The wind tunnel is an closed loop design with total length of 10 m and a 9:1 contraction ratio, a nozzle diameter of 350 mm and test chamber of the height, width, and length of 80 mm, 80 mm and 1000 mm. The air speeds range are 0.2 m/s to 60 m/s in the test section in the contracted section. An inverter is used to control the fan for proper wind speed generation.

The velocity standard used is a LDV placed on a three-axis traversing system, manufactured by DANTEC and a laser wavelength of 514.5 nm.
In order to trace air speed measurement to the International System of Units, (SI).The spinning disk as a velocity standard as shown in figure 2.
Based on the measurements and analysis on the flow in wind tunnel. The expanded uncertainty is estimated under 95% level of confidence. u_{base} = 0.249 %,u_{BED} = 0.04 %,k = 2.06,U_{CMC} = 0.52 %.

Figure 1 the air speed calibration system

Figure 2 the spinning disk

Uncertainty budget of CMS

The uncertainty budget of the CMS air speed standards
The real air speed at the anemometry position can be expressed as

$$V_{\mathrm{tunnel}} = V_{\mathrm{ldv}} \times \delta \times \varepsilon \quad (1)$$

where

V_{ldv} : Air speed measured by using LDV

V_{tunnel} : Real air speed at the position of anemometry

δ : Correction factor for flow characteristic

ε : Correction factor for wind-tunnel performance

According to equation (1), the uncertainty of air speed in the measurement zone can be expressed as

$$u_C^{\,2}(V_{tunnel}) = \left[\frac{\partial f}{\partial V_{ldv}} u(V_{ldv})\right]^2 + \left[\frac{\partial f}{\partial \delta} u(\delta)\right]^2 + \left[\frac{\partial f}{\partial \varepsilon} u(\varepsilon)\right]^2$$

$$u_C^{\,2}(V_{tunnel}) = \left[c_1 u(V_{ldv})\right]^2 + \left[c_2 u(\delta)\right]^2 + \left[c_3 u(\varepsilon)\right]^2 \qquad (2)$$

where
c_1: sensitivity coefficient of the variable V_{ldv} ;
c_2: sensitivity coefficient of the variable δ ;
c_3: sensitivity coefficient of the variable ε ;

The uncertainty of air speed in the measurement zone can be expressed as

$$\frac{u(V_{tunnel})}{V_{tunnel}} = \left(\left(\frac{u(V_{ldv})}{V_{ldv}}\right)^2 + \left(\frac{u(\delta)}{\delta}\right)^2 + \left(\frac{u(\varepsilon)}{\varepsilon}\right)^2\right)^{1/2} \qquad (3)$$

The uncertainty budget of the air speed measurement system is shown in Table 1.

Table 1: Uncertainty Summary Table

Symbol	Uncertainty Source		$u(x_i)/x_i$ (%)	ν_x
$[\frac{u(V_{ldv})}{V_{ldv}}]$	LDV System		0.075	46
$[\frac{u(\delta)}{\delta}]$	Flow and particle influences in LDV measurement		0.056	1067
	1	Particle lag	0	∞
	2	Velocity bias	0.010	∞
	3	Turbulence intensity	0.055	999
	4	Fringe bias	0	∞
$[\frac{u(\varepsilon)}{\varepsilon}]$	Flow velocity distribution in wind Tunnel		0.230	8
	1	Along vertical direction	0.141	14
	2	Along horizontal direction	0.129	7
	3	Axial Velocity direction	0.128	9
$[\frac{u_c(V_{tunnel})}{V_{tunnel}}]$	Combined standard relative uncertainty		0.249	25
k	Coverage Factor		2.06	25
$[\frac{U(V_{tunnel})}{V_{tunnel}}]$	Relative Expanded Uncertainty		0.51	25

A.2. NIM

a. The standard facilities at NIM

The air velocity standard facility was developed at 2009, which locates in the new campus of NIM. The wind tunnel, LDV and spinning-disc facility are taken to make experiments of K3.

i. Wind tunnel

The type of wind tunnel at NIM is open-jet. The specification and facility are shown as Table 1 and the Figure 1.

Table 1 - The specification of wind tunnel

Velocity range	(0.2~30）m/s
Radius of nozzle	R=100 mm
Core region	R=70 mm
Uniformity of profile	0.35 %
Stability of flow	0.35 %
Contraction	9 : 1
Diameter of settling chamber	600 mm
Size of test section	Length1000 mm ,Width 800 mm, Height 800 mm
Diameter of diffuser	300 mm
Type of fan	Axial fan

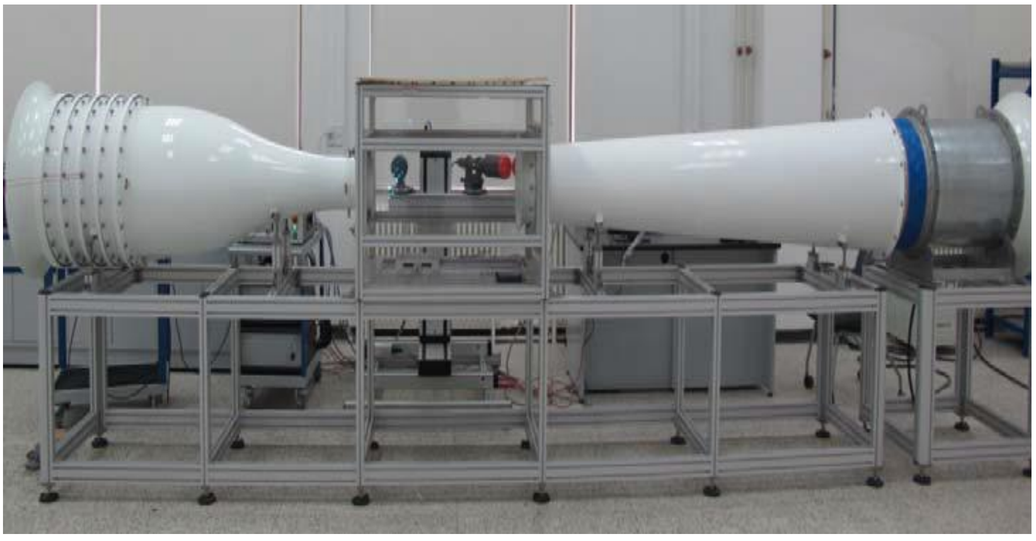


Figure 1 - Wind tunnel

ii. LDV

The LDV for K3 is manufactured by Dantec. The specification is shown as Table 2.

Table 2 - LDV specification

Wave length	514.5 nm
Diameter of front lens	60 mm
Beam distance	39.07 mm
Focus length	800 mm
expander	E=1.98
Scatter particles	DEHS
Diameter of particles	5 μm
Expanded uncertainty	0.24%，k=2

iii. Spinning-disc facility

The spinning-disc for K3 is developed by NIM. The specification and facility are shown as Table 3
and Figure 2.

Table 3 - Specification of spinning-disc facility

Diameter of spinning-disc	200.2848 mm
Velocity range	0.1~30 m/s
Diameter of wire	5 μm

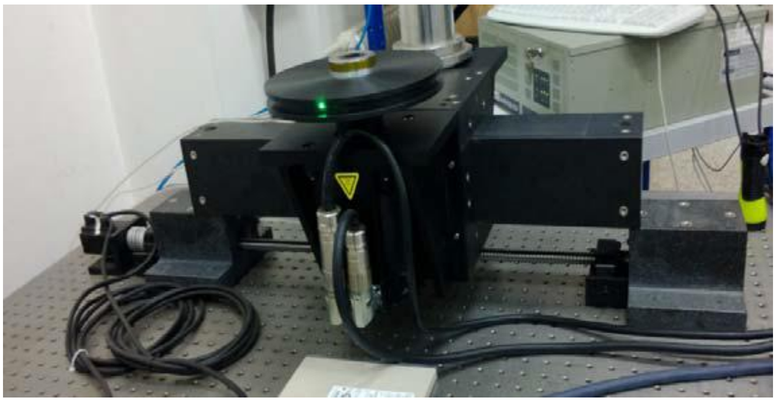


Figure 2 - Spinning-disc facility

A.3. NMC, A*STAR

Calculation of Measurement Uncertainty for APMP.M.FF-K3

1. Measurement equipment

Table 1.1 Summary of measurement equipment and nominal air speeds

Measurement equipment used	Features examined
1) Laser Doppler Anemometer (Serial No.: 102) Measurement Range: 0.2 m/s – 60 m/s 2) Precision Wind-tunnel System (Serial No.: WK818060G) Measurement Range: 0.2 m/s – 60 m/s	Nominal air speeds measured 0.5 m/s 2 m/s 5 m/s 10 m/s 15 m/s 20 m/s 30 m/s

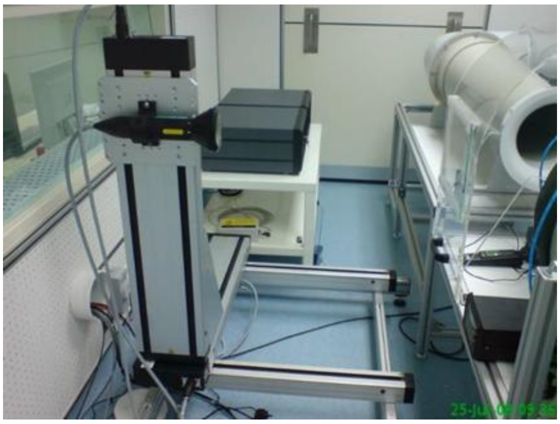


Figure 1. Laser Doppler Anemometer and Precision Wind tunnel

2. Comparison setup

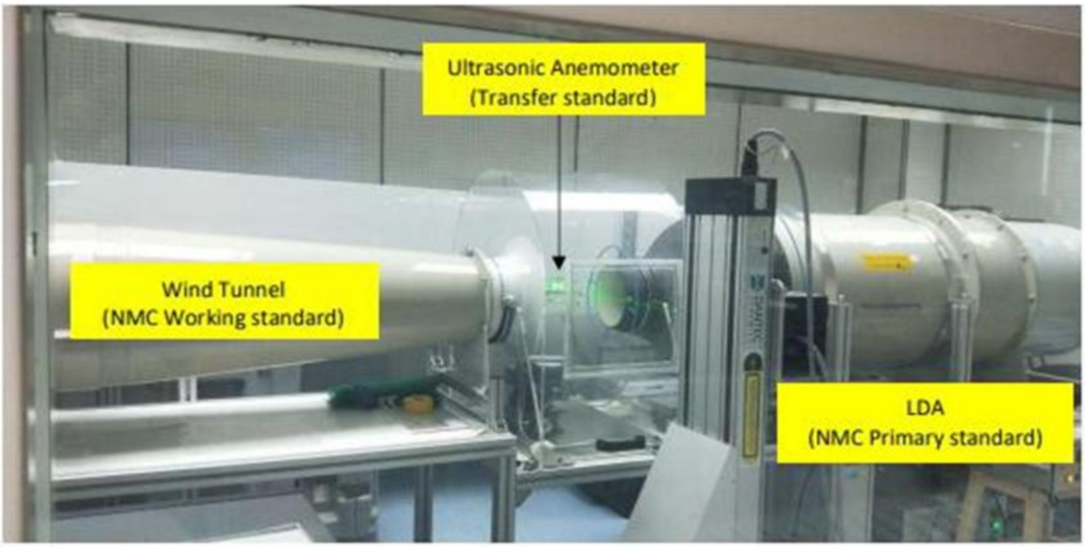


Figure 2. APMP.M.FF.K3.2020 Comparison setup

3. Environmental Condition

The measurements were carried out under the ambient condition of
Temperature: (20 ± 1) ℃
Relative Humidity: (55 ± 10) % relative humidity

4.Calculation of Measurement Uncertainty

The expanded measurement uncertainty calculation is shown as the tables below.

Table 4.1 Expanded measurement uncertainty calculation at 0.5 m/s

S/N	Source of Uncertainty	Symbol	Unit	Uncertainty	Degree of freedom	Sensitivity coefficient	Std Uncertainty (u_i)	
				Relative (%)			*Coverage factor*	Relative (%)
1	Meaurement uncertainty of LDA	V_{LDA}	m/s	0.0058	∞	1	2	0.0029
2	Wind tunnel turbulence and uniformity	K_{td}	-	1.7399	∞	1	$\sqrt{3}$	1.0046
3	Wind tunnel long term stability	K_{wl}	-	0.7300	∞	1	$\sqrt{3}$	0.4215
4	Wind tunnel wind blockage	K_b	-	0.0500	∞	1	$\sqrt{3}$	0.0289
5	Density of air	ρ	kg/m^3	0.1000	∞	$\left\lvert\frac{1}{2\Delta p}\times d\Delta p\right\rvert$	$\sqrt{3}$	0.0577
6	Pressure drop across nozzle	ΔP	Pa	0.1000	∞	$\left\lvert-\frac{1}{2\rho}\times d\rho\right\rvert$	$\sqrt{3}$	0.0577
7	Resolution of UUT	U_{res}	m/s	0.2000	∞	1	$2\sqrt{3}$	0.0577
8	Repeatability of measurement	U_{rep}	m/s	0.6573	4	1	1	0.6573
Combined uncertainty								1.3
Expanded uncertainty at a confidence level of 95% (k=2)								2.6

Table 4.2 Expanded measurement uncertainty calculation at (2 – 10) m/s

S/N	Source of Uncertainty	Symbol	Unit	Uncertainty	Degree of freedom	Sensitivity coefficient	Std Uncertainty (u_i)	
				Relative (%)			*Coverage factor*	Relative (%)
1	Meaurement uncertainty of LDA	V_{LDA}	m/s	0.0058	∞	1	2	0.0029
2	Wind tunnel turbulence and uniformity	K_{td}	-	0.2600	∞	1	$\sqrt{3}$	0.1501
3	Wind tunnel long term stability	K_{wl}	-	0.1500	∞	1	$\sqrt{3}$	0.0866
4	Wind tunnel wind blockage	K_b	-	0.0500	∞	1	$\sqrt{3}$	0.0289
5	Density of air	ρ	kg/m^3	0.1000	∞	$\left\lvert\frac{1}{2\Delta p}\times d\Delta p\right\rvert$	$\sqrt{3}$	0.0577
6	Pressure drop across nozzle	ΔP	Pa	0.1000	∞	$\left\lvert-\frac{1}{2\rho}\times d\rho\right\rvert$	$\sqrt{3}$	0.0577
7	Resolution of UUT	U_{res}	m/s	0.0500	∞	1	$2\sqrt{3}$	0.0144
8	Repeatability of measurement	U_{rep}	m/s	0.1746	4	1	1	0.1746
Combined uncertainty								0.28
Expanded uncertainty at a confidence level of 95% (k=2)								0.56

Table 4.3 Expanded measurement uncertainty calculation at (15 – 30) m/s

S/N	Source of Uncertainty	Symbol	Unit	Uncertainty	Degree of freedom	Sensitivity coefficient	Std Uncertainty (u_i)	
				Relative (%)			*Coverage factor*	Relative (%)
1	Meaurement uncertainty of LDA	V_{LDA}	m/s	0.0077	∞	1	2	0.0038
2	Wind tunnel turbulence and uniformity	K_{td}	-	0.2533	∞	1	$\sqrt{3}$	0.1463
3	Wind tunnel long term stability	K_{wl}	-	0.2000	∞	1	$\sqrt{3}$	0.1155
4	Wind tunnel wind blockage	K_b	-	0.0667	∞	1	$\sqrt{3}$	0.0385
5	Density of air	ρ	kg/m^3	0.1333	∞	$\left\lvert\frac{1}{2\Delta p}\times d\Delta p\right\rvert$	$\sqrt{3}$	0.0770
6	Pressure drop across nozzle	ΔP	Pa	0.0067	∞	$\left\lvert-\frac{1}{2\rho}\times d\rho\right\rvert$	$\sqrt{3}$	0.0038
7	Resolution of UUT	U_{res}	m/s	0.0067	∞	1	$2\sqrt{3}$	0.0192
8	Repeatability of measurement	U_{rep}	m/s	0.0164	4	1	1	0.0164
Combined uncertainty								0.24
Expanded uncertainty at a confidence level of 95% (k=2.00)								0.48

A.4. KRISS

Uncertainty estimation of KRISS air speed system

Figure 1 TS is calibrated by the Pitot tube in KRISS wind tunnel

The model equation of an air speed measurement using pitot tube as follows;

$$v_s = \alpha(1-\varepsilon)\left(\frac{2\Delta p}{\rho}\right)^{1/2} + tu + \Delta v \quad (1)$$

The meaning of symbols in Eq.(1) as follows,

1) Air speed measured by pitot tube: v_s [m/s]
2) Calibration factor of the pitot tube: α [-]
3) Compressibility factor: ε [-]
4) Differential pressure measurements: Δp [Pa]
   - -Differential pressure measured by gauge: Δp_m [Pa]
   - -Blocking effect of the pitot tube: $\delta(\Delta p)$ [Pa]
   - -Pressure loss due to pitot tube: ξ [Pa]
   - -Installation angle of pitot tube: $\varphi(\Delta p)$ [Pa]
5) Density of air: ρ [kg/m^3]
6) Turbulence intensity: tu [m/s]
7) Velocity difference caused by the location of measurement: Δv [m/s]

The uncertainty of the v_s in Eq. (1) yields,

$$u_c(v_s) = \left[c_\alpha^2 u^2(\alpha) + c_\varepsilon^2 u^2(\varepsilon) + c_{\Delta p}^2 u^2(\Delta p) + c_\rho^2 u^2(\rho) + c_{tu}^2 u^2(tu) + c_{\Delta v}^2 u^2(\Delta v)\right]^{1/2} \quad (2)$$

The sensitivity coefficients can be obtained by differentiating Eq. (1).

$$c_\alpha = (1-\varepsilon)\left(\frac{2\Delta p}{\rho}\right)^{1/2} \quad [\mathrm{Pa}^{1/2}\ (\mathrm{kg/m^3})^{-1/2}]$$

$$c_\varepsilon = -\alpha\left(\frac{2\Delta p}{\rho}\right)^{1/2} \quad [\mathrm{Pa}^{1/2}\ (\mathrm{kg/m^3})^{-1/2}]$$

$$c_{\Delta p} = \frac{1}{2}\alpha(1-\varepsilon)\left(\frac{2}{\Delta p\,\rho}\right)^{1/2} \quad [(\text{Pa kg/m}^3)^{-1/2}]$$

$$c_{\rho} = -\frac{1}{2}\alpha(1-\varepsilon)\left(\frac{2\Delta p}{\rho^3}\right)^{1/2} \quad [\text{Pa}^{1/2}\,(\text{kg/m}^3)^{-3/2}]$$

$$c_{tu} = c_{\Delta v} = 1$$

For example, at 15 m/s, Δp is 126.2 Pa, air density is 1.1527 kg/m^3, pitot coefficient is 1.0015 from ISO3966, and the compressibility correction factor $(1-\varepsilon)$ is 0.99977. Then, the sensitivity factors are as follows, in units given above:

$c_\alpha = 15$, $c_{(1-\varepsilon)} = -15$, $c_{\Delta p} = 0.059$, $c_\rho = -6.4$, $c_{tu} = c_{\Delta v} = 1$

The combined standard uncertainty of the velocity measurement using Pitot tube and the degrees of freedom are calculated with the root-sum-square method from the following standard uncertainties in Table 1 and the degrees of freedom.

Table 1 Standard uncertainty of the parameters

Parameter	$u(x_i)$		ν		c_i
	Type A	Type B	Type A	Type B	
α	N/A	2.00E-03	N/A	55	1.5E+01
$(1-\varepsilon)$	4.7E-09	2.9E-07	61	12	-1.5E+01
Δp (Pa)	1.3E-01	1.6E-01	56	10	5.9E-02
ρ (kg/m^3)	1.4E-05	2.5E-04	65	8	-6.4E+00
tu (m/s)	1.6E-03	N/A	10000	N/A	1
Δv (m/s)	2.7E-03	N/A	5	N/A	1

Therefore, the combined uncertainty of v_s can be calculated, $u_c(v_s)$ =3.2×10^{-2} m/s. The effective degrees of freedom is ν_{eff} =72. The coverage factor is 2.0 with 95% confidence level. Final results for v_s =14.9 m/s is v_s =14.9 ± 6.4×10^{-2} m/s. The uncertainty analysis is repeated from 2.0 to 15 m/s including the repeatability of BED. Results are shown in Table 2 and those are the CMC of KRISS air speed measurement. Finally, the calibration uncertainty of TS is calculated by the WGFF guidelines for CMC uncertainty and calibration report uncertainty.

Table 2 Uncertainty of the air speed measurement by Pitot tube

v_s (m/s)	2.04	4.92	9.86	14.91
U_{pitot} (m/s)	1.9E-02	2.2E-02	4.4E-02	6.4E-02
U^*_{pitot} (%)	1.1	0.6	0.6	0.6
k	2	2	2	2
ν_{eff}	18	74	74	72

A.5. NMIJ

Used calibration facility

NMIJ has 3 categories of air speed standard segmented by range now, however, the highest range (40 m/s - 90 m/s) was not provided yet at the key comparison performed in 2013. Figure 1 shows schematics of standard facilities used for the key comparison.

For calibration points less than 1.3 m/s, tow carriage system of low air speed standard was used. The tow carriage travels along the rail trough static air in underground tunnel , and outputs from the DUT is compared with the reference traveling speed determined by laser interferometer. The carriage runs 4 times for each calibration point. To calm the air, the carriage waits 30 minutes for 0.5 m/s and 45 minutes for 1.0 m/s. The carriage runs for opposite directions represented as A and B in Figure 1 (i) to avoid the error caused by background flow through the tunnel.

For other calibration points up to 40 m/s, wind tunnel was used for both transfer anemometers. The wind tunnel of NMIJ is Gottingen type, and has closed test section in square shape. Double pass ultrasonic flow meter fixed just upstream of the measuring point is used as a reference anemometer of the wind tunnel. For LDA measurement, enlarged incense smoke particles were seeded in wind tunnel to detect the scattered light from the air flow.

According to the recommendation in protocol, spinning disc system is also used for the LDA calibration. The spinning disk has 5 μm tungsten wire to simulate the seeding particle. To avoid the error caused by wire bending, the wire orbit diameter is measured by observing the burst signal amplitude with traversing rotor assembly at each calibration speed just before the Doppler frequency measurement. This spinning disc system generates various speeds to treat the whole LDA setup as a black box to include the frequency dependence of the signal processor for calibration result.

Uncertainty budget at NMIJ

The anemometer calibration system at NMIJ consists of an LDV calibrator, an LDV transfer standard and a wind tunnel as shown in Fig. B-1. The schematic of the LVD calibrator and the wind tunnel is illustrated in Figs. B-2 and B-3. The uncertainty budget is shown Table B-1 and B-2.

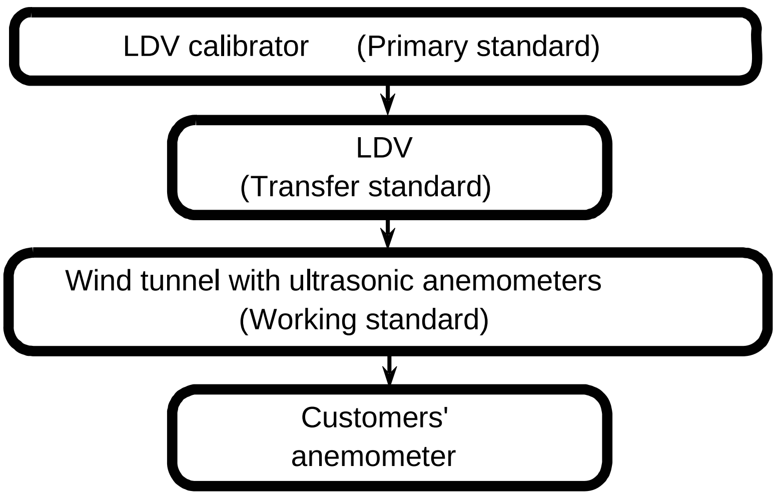
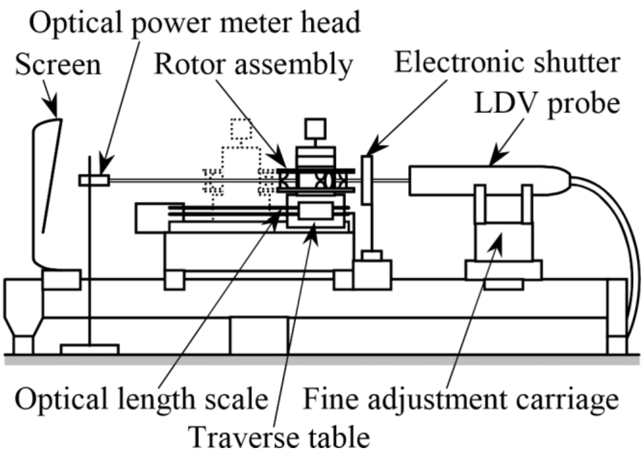
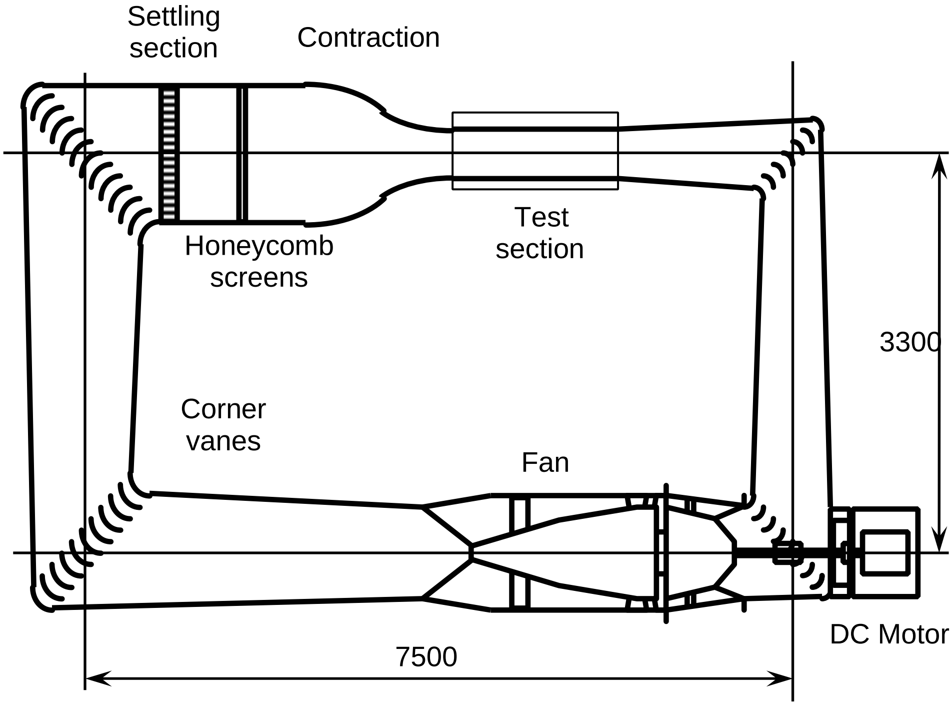


Fig. A-1 Anemometer Calibration System



A-2 LDV Calibrator



A-3 Calibration Wind Tunnel

Table A-1 Uncertainty sources and their sensitivity coefficient

Input quantity	Symbol	Uncertainty source	Sensivity coefficient	Type
Reference air speed	V_{ref}		| 1 |	
	α_{USR}	Correction factor to output value of ultrasonic reference anemometer	| 1 |	B(A)
	S_{meter}	Frontal projected area of DUT	$\left\lvert \frac{S_{\mathrm{meter}}}{S_{\mathrm{WT}} - S_{\mathrm{meter}}} \right\rvert$	A
	S_{WT}	Cross-sectional area of calibration wind tunnel	$\left\lvert \frac{-S_{\mathrm{meter}}}{S_{\mathrm{WT}} - S_{\mathrm{meter}}} \right\rvert$	A
	$U_{\mathrm{USR*}}$	Output of ultrasonic reference anemometer when DUT is installed at the test section	$\left\lvert \frac{U_{\mathrm{USR*}}}{U_{\mathrm{corrctd*}}} \right\rvert$	A
	$U_{\mathrm{USR0*}}$	Output of ultrasonic reference anemometer at zero air speed	$\left\lvert \frac{U_{\mathrm{USR0*}}}{U_{\mathrm{corrctd*}}} \right\rvert$	A
Repeatability of DUT	V_{m}		| -1 |	

Table A-2 Uncertainty budget (Symbols are defined in Table A-1)

Uncertainty sources	Air speed range												Unit
	1.3≤ ≤ 1.5	1.5< ≤ 2	2< ≤ 3	3< ≤ 5	5< ≤ 7	7< ≤ 10	10< ≤ 15	15< ≤ 20	20< ≤ 25	25< ≤ 30	30< ≤ 35	35< ≤ 40	m/s
V_{ref}	0.304	0.23	0.169	0.148	0.144	0.147	0.147	0.143	0.145	0.145	0.169	0.169	%
α_{USR}	0.303	0.229	0.169	0.148	0.143	0.147	0.147	0.143	0.145	0.145	0.169	0.169	%
S_{meter}	9.5 x10-03	9.5 x10-03	9.5 x10-03	9.5 x10-03	9.5 x10-03	9.5 x10-03	9.5 x10-03	9.5 x10-03	9.5 x10-03	9.5 x10-03	9.5 x10-03	9.5 x10-03	%
S_{WT}	9.5 x10-03	9.5 x10-03	9.5 x10-03	9.5 x10-03	9.5 x10-03	9.5 x10-03	9.5 x10-03	9.5 x10-03	9.5 x10-03	9.5 x10-03	9.5 x10-03	9.5 x10-03	%
$U_{\mathrm{USR*}}$	2.4 x10-04	2.4 x10-04	2.1 x10-04	2.8 x10-04	5.5 x10-04	7.5 x10-04	0.001	0.001	0.002	0.002	0.002	0.003	m/s
$U_{\mathrm{USR0*}}$	1.7 x10-04	1.7 x10-04	1.7 x10-04	1.7 x10-04	1.7 x10-04	1.7 x10-04	1.7 x10-04	1.7 x10-04	1.7 x10-04	1.7 x10-04	1.7 x10-04	1.7 x10-04	m/s
V_{m}	0.145	0.124	0.104	0.073	0.043	0.031	0.03	0.03	0.029	0.033	0.035	0.035	%
x	1	1	1	1	1	1	1	1	1	1	1	1	—
$u(x)$	0.003	0.003	0.002	0.002	0.001	0.001	0.001	0.001	0.001	0.001	0.002	0.002	—
$\frac{u(x)}{\lvert x \rvert}$	0.336	0.261	0.198	0.165	0.15	0.15	0.15	0.146	0.147	0.149	0.173	0.173	%
$\frac{U(x)}{x}$	0.673	0.523	0.397	0.331	0.3	0.299	0.299	0.292	0.294	0.298	0.346	0.346	%

A.6. NIMT

Calibration facility for air speed anemometers

The wind tunnel system of NIMT is Göttingen type which constructed as a closed return wind-tunnel system and open test-section. A thermo electrical and Pitot tube anemometers are installed to control the speed of motor by locating away from the nozzle outlet and the wall of nozzle about 20 mm. In the process of the ultrasonic anemometer calibration, the temperature-controlled system is used to control the stability of the temperature.

Laser Doppler Anemometer (LDA), calibrated by PTB, is used as the transfer standard to participate in the comparison, APMP.M. FF-K3.2020.

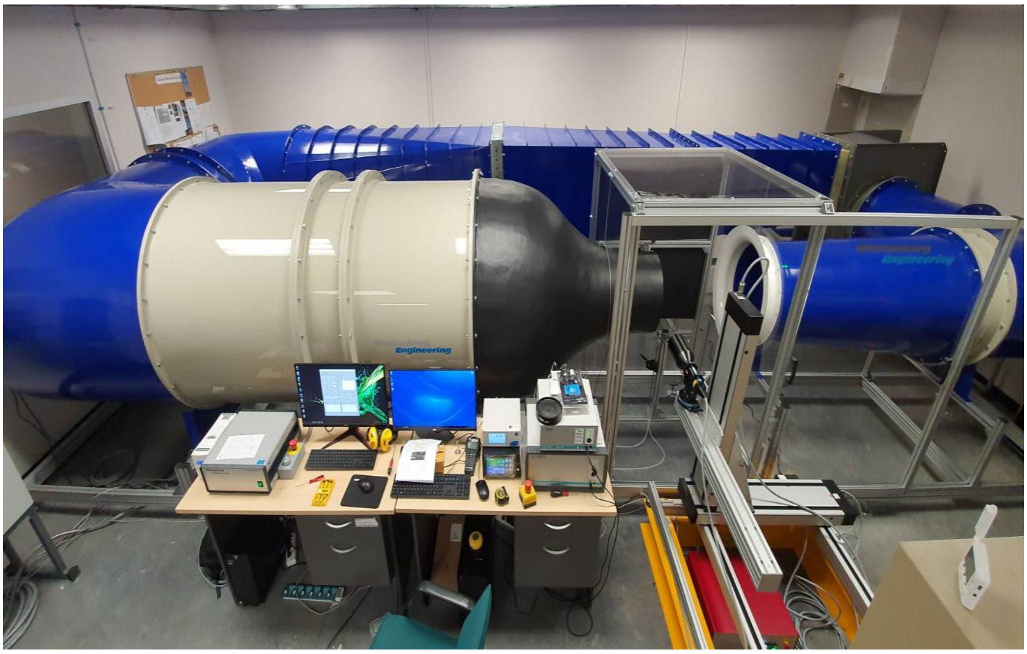


Figure 2. Closed loop wind tunnel

The general information of NIMT's air velocity standard can be shown in table 1.

Table 1. General information of the air velocity standard at NIMT

Type	Göttingen, closed loop and open test section
Range	0.1 to 50 m/s
CMC	0.5%
Diameter	450 mm
Test section length	630 mm
Reference standard	Lase Doppler Anemometer, LDA Focal length 800 mm and 500 mm

Traceability	PTB

1. Installation of the ultrasonic anemometer

The ultrasonic anemometer which is performed as the transfer standard is installed on an appropriate clamp at 250 mm away from the middle of wind tunnel nozzle outlet (Figure 2). The Laser Doppler Anemometer (LDA) is installed on the automatic traversing mechanism system at 50 mm away from the nozzle.

The velocity standard which is measured by LDA is compensated by the correction factor due to the velocity profile along the flow direction. The ratio between the nozzle outlet area and projected area of the transfer standard is small , therefore no blockage correction is applied.

Figure 2. Set-up of the ultrasonic anemometer

2. Mathematical model

The K coefficient can be determined as,

$$K = k_c \cdot \frac{v_{\text{std}}}{v_{\text{uuc}}} + \delta K(v_{\text{long-term, std}}) + \delta K(v_{\text{shot-term, std.}}) + \delta K(k_c) + \delta K(v_{\text{res, std}}) + \ldots.$$

$$\ldots.. + \delta K(\delta v_{\text{shot-term,uuc}}) + \delta K(\delta v_{\text{res, uuc}}) + \delta K(\delta v_{\text{A}})$$

where

k_c is the correction factor due to the velocity profile along the flow direction,

v_{std} is the air velocity reading by LDA,

v_{uuc} is the air velocity reading by the ultrasonic anemometer,

$\delta K(v_{\text{long-term, std}})$ is the correction of K coefficient due to the long-term stability of LDA,

$\delta K(v_{\text{shot-term, std}})$ is the correction of K coefficient due to the short-term stability of LDA,

$\delta K(k_c)$ is the correction of K coefficient due to the correction factor of the velocity profile along the flow direction,

$\delta K(v_{\text{res, std}})$ is the correction of K coefficient due to the resolution of LDA,

$\delta K(v_{\text{shot-term, uuc}})$ is the correction of K coefficient due to the short-term stability of the ultrasonic anemometer,

$\delta K(v_{\text{res, uuc}})$ is the correction of K coefficient due to the resolution of the ultrasonic anemometer,

$\delta K(v_A)$ is the correction of K coefficient due to the repeatability.

3. Uncertainty evaluation

Example of the uncertainty budget at 0.5 m/s

Quantity	**Estimation**		**Standard uncertainty**		**Probability distribution**	**Divisor**	**Sensitivity coefficient**	**Uncertainty contribution**	ν_i **or** ν_{eff}
X_i	x_i		$u(x_i)$				c_i	$u_i(y)$	
v_{uuc}	0.472	m/s	-	-	-	-	-	-	-
v_{std}	0.4990	m/s	0.190	%	N	2	0.01058	0.00201	∞
$\delta v_{\text{long-term,std}}$	0	m/s	0.1097	%	R	$\sqrt{3}$	0.01058	0.00116	∞
$\delta v_{\text{short-term,std}}$	0	m/s	0.00010	m/s	N	1	2.1208	0.000208	1257
$\delta v_{\text{corr., std}}$	1.0010		0.00116		N	1	1.0572	0.00123	9
$\delta v_{\text{res,std}}$	0	m/s	0.000029	m/s	R	$\sqrt{3}$	2.1208	0.0000612	∞
$\delta v_{\text{short-term,uuc}}$	0	m/s	0.002221	m/s	N	1	2.2421	0.00498	59
$\delta v_{\text{res,uuc}}$	0	m/s	0.00029	m/s	R	$\sqrt{3}$	2.2421	0.000647	∞
δv_A	0		0.00161		N	1	1	0.00161	4
$K = v_{std}/v_{uuc}$	1.0583						u =	0.0059	98
					k =	2.03	U =	**0.0119**	

A.7. VMI

I. SYSTEM DESCRIPTIONS

Towards the end of 2019, Vietnam Metrology Institute (VMI) began operating an airspeed system to provide calibration services for airspeed instruments such as static Pitot tubes and anemometers of various types, including hot-wire, ultrasonic, and others. The system consists of a test section, wind tunnel and an LDA airspeed measurement system. The wind tunnel is a closed-circuit facility lying in a horizontal. This tunnel was developed by the company Westenberg Engineering GmbH. The system works at around ambient pressure and temperature. The test section is an open type with a length of 468 mm and a diameter of 320 mm for the nozzle. VMI's airspeed system has a velocity range of 0.3 m/s to 70.0 m/s with a relative expanded uncertainty (k=2) of 0.5 %. Figure 1 illustrates the airspeed standard system with transfer standard in the test section.Figure 1: VMI's primary airspeed standard system

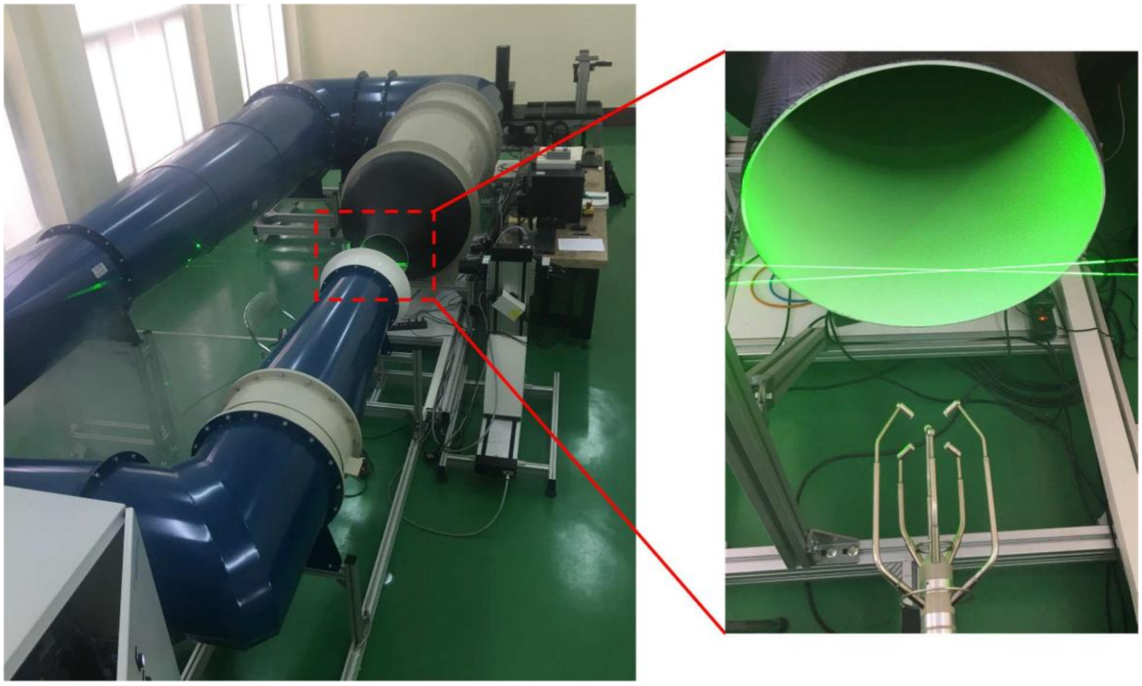


Figure 1: VMI's primary airspeed standard system

The velocity standard used is a Laser Dopole Anemometry (LDA) system placed on a two-axis traversing system, as shown in Figure 2(A). This means that traceability is accomplished indirectly by using LDA method. The LDA uses a Dantec burst spectrum analyzer (BSA) to determine the Doppler frequency of the scattered light. To generate the particles used in the light scattering process, smoke droplets are introduced into the wind tunnel via the combustion of special Dantec-supplied oil. The light scattering is achieved through the use of a laser source with a power of 150 mW and wavelengths of 532nm and 561nm. Detailed specifications of the wind tunnel and the LDA system can be found in Table 1.

Table 1: Main specifications of the airspeed system

Wind tunnel	
Type	Closed-loop circuit
Manufacture	Westenberg Engineering GmbH
Range of operating velocity	0.3 to 70.0 $m.s^{-1}$
Expanded uncertainty (P~ 95%, k =2)	0.5 %
Dimensions of test section	diameter of the nozzle: 320 mm
	Contraction ratio: 8
	Length of test-section: 468 mm
	diameter of the diffuser: 390 mm
Embient conditions	(20 ± 2) ^{o}C
	(900 ÷ 1000) hPa
	(60 ÷750) %
References instrument	Hot-wire of TSI (for velocity < 5 $m.s^{-1}$)
	Pitot-tube (for velocity ≥ 5 $m.s^{-1}$)
	LDA: Flow explorer DPSS system by Dantec Dinamics - Denmark
LDA	
Laser power	150 mW
Laser wavelengths	532 and 561 nm
Focal length	500 nm
Probe volume length	3.1 mm

The LDA system's velocities have been calibrated against a rotating glass cylinder with a known rotational speed and radius, as shown in Figure 2(B). To produce scattered light from the intersection volume formed by coherent laser beams, the small particles have adhered to the glass cylinder's surface. The rotating glass cylinder's surface velocity is determined using counted impulses, measured time, and the cylinder's precise known radius. The rotating cylinder system is described in detail in Table 2.

Table 2: Main specifications of the spinning-cylinder system

Material of the cylinder	Glass
Manufacture	ILA - GmbH
Diameter	50 mm
Velocity	(0 ÷ 4.5) $m.s^{-1}$

Single impulse	18000 (puls.rev^{-1})
Clock	$(2*10^6 \pm 25*10^{-6})$ Hz

II. MEASUREMENT PROCEDURE

1. Installation

Figure 3 depicts the installation of the ultrasonic meter in the test section of the wind tunnel. In this case, the ultrasonic meter was positioned 270 mm from the nozzle outlet. The airspeed standard system was used to establish the seven velocity values, including 0.5, 2, 5, 10, 15, 20, 30 m/s. Each minute, velocity values were recorded simultaneously at the LDA and the ultrasonic meter at each velocity setpoint. This procedure was repeated five times for each velocity.

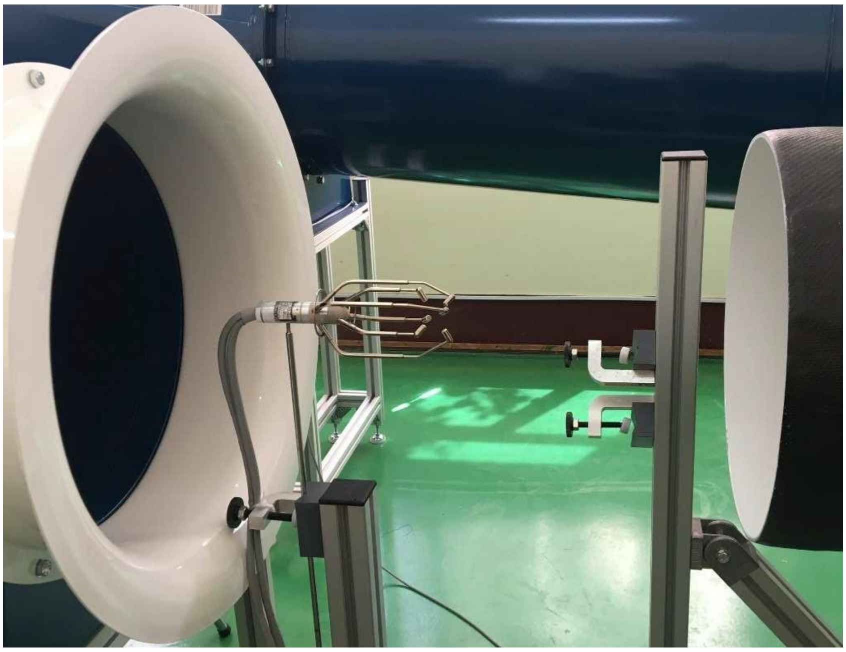


Figure 3: Installed position of ultrasonic meter in test secton

2. Uncertainty budgets

The following equation expresses the calibration factor (K) of the ultrasonic meter using LDA in the wind tunnel:

$$K = \frac{V_{ref}^{corr.}}{V_{Ult}} \qquad (1)$$

Where:

K: Calibratiton factor of the ultrasonic meter.

$_{ref}^{corr.}$: Corrected velocity at LDA, m/s.

V_{Ult}: indicated velocity at the ultrasonic meter, m/s.

In this case, corrected velocity at LDA refers to the velocity at LDA after taking into account the effects of factors such as blockage factor, the change of the velocity in the horizontal direction in the test section, and velocity stability in the test section, etc. This velocity can be expressed as below equation:

$$V_{ref}^{corr.} = V_{LDA} * k_{blk} * k_{Flo} * k_{Per} * k_{stb} \tag{2}$$

Where:

u_A: relative uncertainty type A, %;

u_{LDA}: relative uncertainty of LDA, %;

u_{blk}: relative uncertainty of the correction factor k_{blk}, %;

u_{Flo}: relative uncertainty of the correction factor k_{Flo}, %;

u_{Per}: relative uncertainty of the correction factor k_{Per}, %; u_{stb}: relative uncertainty of the correction factor k_{stb}, %;

u_{res}: relative uncertainty due to the resolution of the ultrasonic meter, %;

At each velocity, the relative combined uncertainty is evaluated according to equation (2) can be express as below:

$$u_c = \sqrt{u_A^2 + u_{LDA}^2 + u_{blk}^2 + u_{Flo}^2 + u_{Per}^2 + u_{stb}^2 + u_{res}^2 + u_{zero}^2} \tag{3}$$

Where:

u_A: relative uncertainty type A, %;

u_{LDA}: relative uncertainty of LDA, %;

u_{blk}: relative uncertainty of the correction factor k_{blk}, %;

u_{Flo}: relative uncertainty of the correction factor k_{Flo}, %;

u_{Per}: relative uncertainty of the correction factor k_{Per}, %;

u_{stb}: relative uncertainty of the correction factor k_{stb}, %;

u_{res}: relative uncertainty due to the resolution of the ultrasonic meter, %;

u_{zero}: relative uncertainty due to the zero value of the ultrasonic meter, %.

Expanded uncertainty U (%) is given by following equation:

$$U = k * u_c \tag{4}$$

where:

k: coverage factor, k = 2 with confidence level of 95%.