Final report on the bilateral CIPM Key Comparison for natural gas at high pressure conducted in October 2006
CCM.FF-K5.a.1

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1 INTRODUCTION

The CIPM and its office the BIPM decided, in accordance with the CIPM Mutual Recognition Arrangement (MRA), to conduct Key Comparisons (KCs) among national primary standards in the subject field high-pressure gases. This includes natural gas and compressed air and/or Nitrogen.

In November to October 2004 the first Key Comparison (KC) for natural gas at high pressure was conducted by PTB Germany, NMi-VSL Netherlands and LNE France. The results were finally documented in the protocol of the CCM.FF-K5.a [1] in August 2005 which was approved by the CCM and the BIPM and has been published at the KCDB of the BIPM in January 2006. The Key Comparison Reference Value of K5.a has been approved by all metrological authorities.

The high-pressure test facility of TransCanada Calibrations (in the following abbreviated as NRC-TCC) has been nominated as responsible for the Canadian national standard for the natural gas flow by the National Research Council of Canada Institute for National Measurement Standards (NRC-INMS). The purpose of this test report is to demonstrate the degree of equivalence of the Canadian standard NRC-TCC with the CIPM-KCRV for the natural gas cubic meter. In order to do that, a bilateral Key Comparison has been organized between NRC-TCC and PTB.

2 THE PRINCIPLES OF THIS INTERCOMPARISON

2.1 The situation of the traceability chains

The German high-pressure national standard PTB-***pigsar***^{TM} has been selected as the comparison partner with NRC-TCC.

In 1999, PTB and NMi-VSL (Netherlands) agreed to establish a common (harmonised) reference value based on regular intercomparisons in accordance to rules for BIPM key comparisons and to disseminate this value. The French LNE joined this agreement in the year 2004. Since May 2004, the harmonised value among PTB, NMi-VSL and LNE is called the European Harmonised Reference (EHRV) value and is disseminated by the test facilities of all three partners, including PTB-***pigsar***^{TM}.

The procedure of harmonisation PTB-LNE-NMi-VSL was done in the form of an authorized CIPM key comparison in the year 2005. As the outcome of this key comparison was approved by the CCM, the EHRV is actually identical with the CIPM Key Comparison Reference Value (KCRV) and is described in all details in the protocol of the CCM.FF-K5.a [1].

The Canadian high-pressure national test facility NRC-TCC has recently been made traceable to the European Harmonized Reference Value (EHRV) through NMi-VSL in the Netherlands. Hence, the test facility of TCC is directly to the KCRV of CCM.FF-K5.a, as explained above.

Therefore, the purpose of this CIPM Key Comparison, CCM.FF-K5.a.1 is to show the degree of equivalence and consistency of the Canadian national test facility NRC-

TCC with the European Harmonized Reference Value (or, equivalently, with the CIPM KCRV of the previous CCM.FF-K5.a).

As TCC depends fully on the European Harmonized Reference Value (EHRV), this actual CCM.FF-K5.a.1 will not establish a new KCRV but will demonstrate the consistency of TCC calibrations with the existing KCRV of FF-K5.a, following a similar protocol. For the evaluation of the intercomparison results it is necessary to consider the dependence (correlation or covariance rsp.) of both participants, PTB-***pigsar***^{TM} and TCC, due to their common reference (the KCRV of CCM.FF-K5.a). This is explained in the following chapter 2.2.

Fig. 1 explains the relations of the partners to the KCRV.

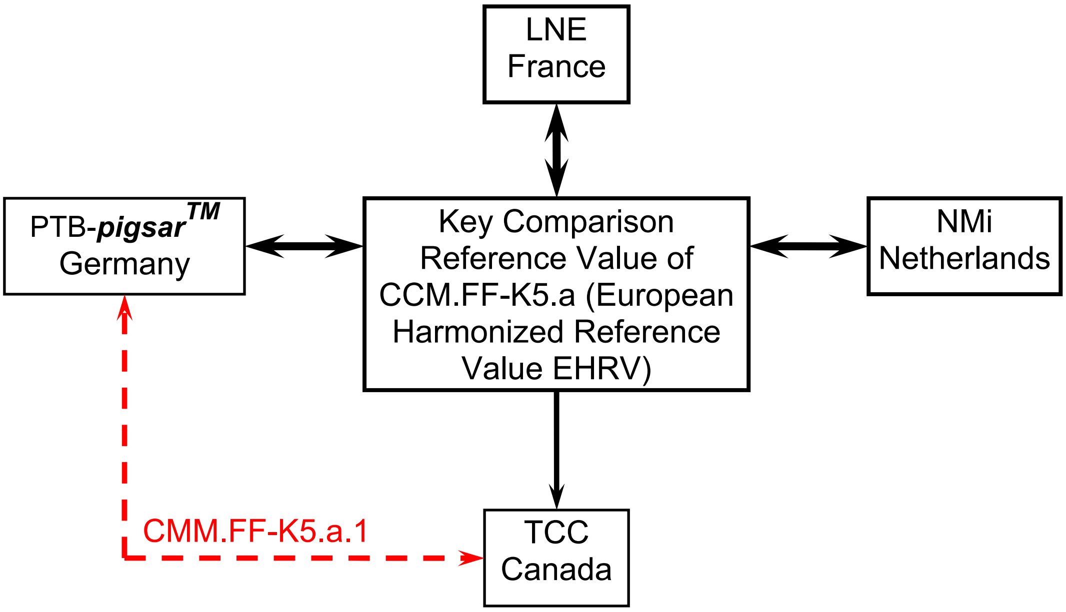

Fig. 1: The traceability of the participants in relation to the Reference Value of CCM.FF-K5.a and the position of the bilateral CCM.FF-K5.a.1

2.2 The evaluation of key comparison data of facilities with common source of traceability

In any key comparison, the differences d_i between the measured result x_i of a participating laboratory i and the key comparison reference value KCRV, x_{KCRV}, have to be calculated according to

$$d_i = x_i - x_{KCRV} \tag{1}$$

As a practical matter, it is often interesting to calculate the statistic E_i

$$E_i = \left| \frac{d_i}{U(d_i)} \right| \tag{2}$$

were $U(d_\mathrm{i})$ is the expanded uncertainty (k = 2) of the difference d_i.

The two quantities, d_i and <u>$U(d_i)$ are referred to as Degrees of Equivalence. (DoE)</u>

The DoE is a measure for the equivalence of the results of any laboratory with the KCRV:

- We consider that the results of a laboratory are ***equivalent if 1 < E_i***.

- The results of a laboratory are ***not equivalent if E_i or E_{ij} >1.2***.

- For values of E_i in the range ***1 < E_i and E_{ij} ≤ 1.2*** a so-called "**warning** level" is reached and some metrological actions are recommended to check the laboratory. The reason for such a "warning level" is that we have to consider the confidence in the determination of the uncertainties (for the results of labs as well the KCRV). Conventionally we work at a 95% confidence level. Therefore in some intercomparisons a range up to E < 1.5 is used for these "warnings" [2] [3]. This is a reasonable value if stochastic influences dominate the uncertainty budgets. In the case of intercomparisons for gas flow, the smaller value 1.2 was chosen which reflects the dominance of non-stochastic parts of uncertainty compared to the stochastic parts (the reproducibility is usually much better than the total uncertainty of a laboratory) [1].

The calculation of the DoE requires the uncertainty of the differences d_i according to eq. (2). To make statements about this, let us consider first the general problem of the difference of two values x_1 and x_2. If we look to the pure propagation of (standard) uncertainty we find:

$$u_{x_1-x_2}^2 = \begin{pmatrix} \dfrac{\partial(x_1-x_2)}{\partial x_1} & \dfrac{\partial(x_1-x_2)}{\partial x_2} \end{pmatrix} \begin{pmatrix} u_1^2 & \mathrm{cov} \\ \mathrm{cov} & u_2^2 \end{pmatrix} \begin{pmatrix} \dfrac{\partial(x_1-x_2)}{\partial x_1} \\ \dfrac{\partial(x_1-x_2)}{\partial x_2} \end{pmatrix} = u_1^2 + u_2^2 - 2\,\mathrm{cov} \qquad (3)$$

In the case of this key comparison, the results of the participants are correlated due to the common traceability to the Key Comparison Reference Value of CCM.FF-K.5.a. The correlation leads to a significant covariance between the measurement results which have to be considered in eq. (3).

The pilot laboratory PTB-***pigsar***$^{\mathbf{TM}}$ is harmonised with this reference value according to the procedures described in the annex (chapter 9) to the protocol of the CCM.FF-K5.a [1].

NRC-TCC has been made traceable by NMi-VSL to the EHRV, which is in the same way harmonised with the KCRV of CCM.FF-K5.a as is the pilot laboratory, PTB-***pigsar***$^{\mathbf{TM}}$

The correlation between the NMi-VSL and PTB-***pigsar***$^{\mathbf{TM}}$ is a consequence of the harmonisation process. The calculation is given in all details in the annex (chapter 9) of the protocol to CCM.FF-K5.a [1]. It is an outcome of this calculation that the covariance can be determined by the following equation (4):

$$\mathrm{cov}_{PTB,NMi} = (r_{PTB} + r_{NMi} - 1)\cdot u_{KRCV-KC5a}^2 < u_{KRCV-KC5a}^2 \qquad (4)$$

were r_{PTB} and r_{NMi} are the correlation coefficients of results given by the relation of the reproducibility u_{repro} and the total uncertainty u_{CMC} of the facilities as recorded in the CMC tables of the BIPM Key Comparison DataBase:

$$r_{PTB} = 1 - \frac{u^2_{repro,PTB}}{u^2_{CMC,PTB}} \quad \text{and} \quad r_{NMi} = 1 - \frac{u^2_{repro,NMi}}{u^2_{CMC,NMi}} \qquad (5)$$

Looking to the numbers of reproducibility e.g. in chapter 3.3 or the annex of the K5.a-protocol we can find that the values of the correlation coefficient r are not far from unity. Therefore it is a realistic conservative estimation to use the upper limit for the covariance which is the square of the uncertainty $u_{\text{KCRV-K5.a}}$ of the KCRV of K5.a. This covariance is of course given during the traceability process from NMi-VSL to NRC-TCC.

Hence, the conservative estimation for the uncertainty of the difference of the results of TCC to the Reference Value of K5.a.1 is:

$$u(d_i) = \sqrt{u^2_{\text{Ref.Val.KC5a.1}} + u^2_{\text{TCC}} - 2u^2_{\text{KCRV-KC5a}}} \qquad (6)$$

The equations (3) and (6) use standard uncertainties (k = 1).

2.3 Intercomparison via Reynolds number

In the previous key comparison CCM.FF-K5.a it was decided to use a couple of single results for the determination of the KCRV which were measured at the same flow rate and same pressure (with small deviations of about 5% and less). Therefore it was not necessary to reflect much about the behaviour of the meter deviation versus flow rate, pressure or Reynolds number.

In contrast to that situation, this KC, CCM.FF-K5.a.1 is performed to determine the degree of equivalence of two partners, which have significantly different pressure levels, i.e. p_{PTB} = 5.0 MPa and p_{TCC} = 6.3 MPa. This difference of about 25% in pressure makes it necessary to expand /enhance the intercomparison procedure.

Due to previous long-time experience with turbine meter calibrations, it was decided to treat the measured results by using a Reynolds number based evaluation for turbine meter readings (meter deviations). In the present case this is particularly appropriate as the Reynolds numbers at NRC-TCC and PTB-***pigsar***^{TM} are quite close together even at the existing pressures differences (due to the gas properties). The different main characteristics for the gas behaviour, composition and Reynolds numbers are given in Tab. 1.

Tab. 1: Main characteristics of the gas used by the participants of KC5a.1 and representative values of Reynolds numbers

Value	PTB-***pigsar***^{TM}	NRC-TCC	Unit
Pressure p	5.01	6.3	MPa
Temperature T	289.35	300.15	K
dynamic Viscosity μ	1.27E-05	1.30E-05	Pa·s
normal density ρ_N (101.325 kPa, 273.15K)	0.815	0.7457	kg/m^3
compressibility-factor K	0.897	0.898	

calorific value H	36.9	37.35	MJ/m^3
Density ρ	42.41	46.99	kg/m^3
typical molar fraction			
CH_4	85.95%	96.04%	
N_2	8.84%	1.84%	
CO_2	1.78%	0.60%	
C_2H_6	2.72%	1.37%	
C_3H_8	0.53%	0.12%	
n-C_4H_{10}	0.07%	0.01%	
i-C_4H_{10}	0.06%	0.01%	
n-C_5H_{12}	0.01%	0.00%	
i-C_5H_{12}	0.01%	0.00%	
n-C_6H_{14} and higher	0.02%	0.00%	
H_2	0.00%	0.00%	
Re at 1000 m^3/h	7.874E+06	8.522E+06	
rel. diff. $Re_{1000m3/h,TCC}/Re_{1000m3/h,PTB}-1$		8.2%	
Q_{max} in the intercomparison	1274	1243	m^3/h
rel. diff. $Q_{max,TCC}/Q_{max,PTB}-1$		-2.4%	
Re at Q_{max}	1.003E+07	1.059E+07	
rel. diff. $Re_{max,TCC}/Re_{max,PTB}-1$		5.6%	

The measurand for intercomparison is the meter deviation f defined as:

meter deviation $f = (\text{Volume}_{\text{Indicated}}/\text{Volume}_{\text{Reference}}-1)*100\%$

Common practice for turbine meter calibration at high pressure is to describe the meter deviation as a polynomial function versus the logarithm of the Reynolds number as given by eq. (7). Hence, we will represent the Key Comparison Reference Value of K5.a.1 in form of a function depending on Reynolds number in the following way:

$$f_{\text{Ref.Val.KC5a.1}} = \sum_{i=0}^{n} a_i \cdot \log^i(\text{Re}) \qquad (7)$$

This function is linear in the coefficients a_i and therefore these coefficients can be determined by using the Least-Square-Approximation-Methods. It has to be taken into account, that in many calibration facilities the single measured values are often correlated. This is very important for the outcome of the approximation process, especially for the resulting uncertainty of the fitted function.

It depends on the general behaviour of the meter and the range of Reynolds number measured, which degree of polynomial is significant for an appropriate fit. This can be determined by conventional statistical methods based on the F-Test for significance. In practice we find degrees between 3 and 5 for the most of the meters to which eq. (7) applies.

Based on the description of the Reference Value of K5.a.1 according to eq. (7), we will determine the difference of the single values f_{TCC} measured by NRC-TCC for each Reynolds number used at NRC-TCC according to eq. (8)

$$d_{TCC-Ref.Val.KC5a.1} = f_{TCC} - f_{Ref.Val.KC5a.1} \tag{8}$$

The coefficients a_i of $f_{Ref.Val.KC5a.1}$ as well as the proof of equivalence with the existing Key Comparison Reference Value of K5.a will be shown in chapter 3.2 below.

3 THE TRANSFER PACKAGE

3.1 The meters (technical description)

The transfer package consists of two parts where each part is equipped with a turbine meter.

Each meter is provided with its own inlet and outlet sections, referred to as part #1 and part #2. Both meters are equipped with NOVA flow straighteners.

Size ($Q_{max\ nominal}$, Diameter): 1000 m^3/h; DN = 150 mm (= 6 “)
Total length of package: 34 D = 5,1 m

Type of meter 1:	turbine G650
Manufacturer:	Elster-Instromet
Serial number:	83034949
Length of part 1: (inlet, meter 1, outlet)	10D; 3D; 3D;

Type of meter 2:	turbine G650
Manufacturer:	RMG
Serial number:	24546
Length of part 2: (inlet, meter 2, outlet)	10D; 3D; 3D;

The meter Elster-Instromet-83034949 of part #1 is the identical artifact also used in the CCM.FF-K5.a [1]. Using this meter here again, we could make sure that the results of the K5.a.1 are linked to the K5.a.

A photo of the transfer package #3 DN 150 mm (=6’’) is presented in the following Fig. 2.

Fig. 2: Photos of the transfer meters. Left hand side shows the G650 Elster-Instromet turbine DN 150 (6'').On the right hand side the DN 150 type RMG G650 (6'') turbine is documented. Both meters have been used including inlet and outlet sections and have been isolates by a flow straightener. Total length of each meter set is 16D. The Elster-Instromet meter set has been used in the previous CCM.FF-K5.a Key Comparison

3.2 The measurement program and the calibration of transfer package with the CIPM Key Comparison Reference Value (Equivalence between KCRV-K5.a and Ref.Val. K5.a.1)

The measurement program for this intercomparison has been agreed and fixed as given in Tab 2 below. As mentioned above, the intercomparison can best be evaluated using a polynomial fit versus Reynolds number using the different single results at the pilot lab. Therefore pressure loads 1.6 MPa and 3.5 MPa were also used at the pilot lab to document a sufficient behaviour of the meters and to ensure a reliable representation of the meter deviations using eq. (7).

Tab. 2: Flow rates and pressures used within the key comparison CCM.FF-K5.a.1

Flow rate [m³/h] (actual conditions)	pressure [MPa]			
	PTB-***pigsar***™			NRC-TCC
	1.6	3.5	5.0	6.3
65	**X**	**X**	**X**	**X**
100	**X**	**X**	**X**	**X**
160	**X**	**X**	**X**	**X**
250	**X**	**X**	**X**	**X**
400	**X**	**X**	**X**	**X**
650	**X**	**X**	**X**	**X**
1000	**X**	**X**	**X**	**X**
1250	**X**	**X**	**X**	**X**
	Single results of measurements are used for the determination of the coefficients in eq. (9) using Least-Square-Approximation			

To determine and document the stability over time of the transfer package used in the intercomparison, the transfer package was tested several times at the pilot laboratory before and after the NRC-TCC calibrations in order to detect any meter shift. Tab. 3 gives a complete overview to all dates of measurements: Because the K5.a.1-Meter #1 was also a part of the transfer package within the previous CCM.FF-K5.a, these previous measurement series are also included in Tab. 3.

Tab. 3: Dates of measurements and pressures used within the key comparisons

Measurement series	**Pressure (MPa)** Date of measurement			
CCM.FF-K5.a	**1.0**	**2.0**	**4.7**	**--**
	Okt. 2004 – Dec. 2004 (LNE/NMi/PTB)			
CCM.FF-K5.a.1	**1.6**	**3.5**	**5.0**	**6.3**
K5a.1 - PTB #1	--	--	2006-05-17	--
K5a.1 - PTB #2	2006-05-26	2006-05-24	2006-05-24	--
K5a.1 - PTB #3	--	--	2006-06-10	--
K5a.1 - PTB #4	2006-06-22	--	2006-06-22	--
K5a.1 – NRC-**TCC**				2006-10-24
K5a.1 - PTB #5	--	--	2006-12-08	

The following graphs in Fig. 3 and Fig 4 document the different individual results of measurements at the pilot lab using the transfer package.

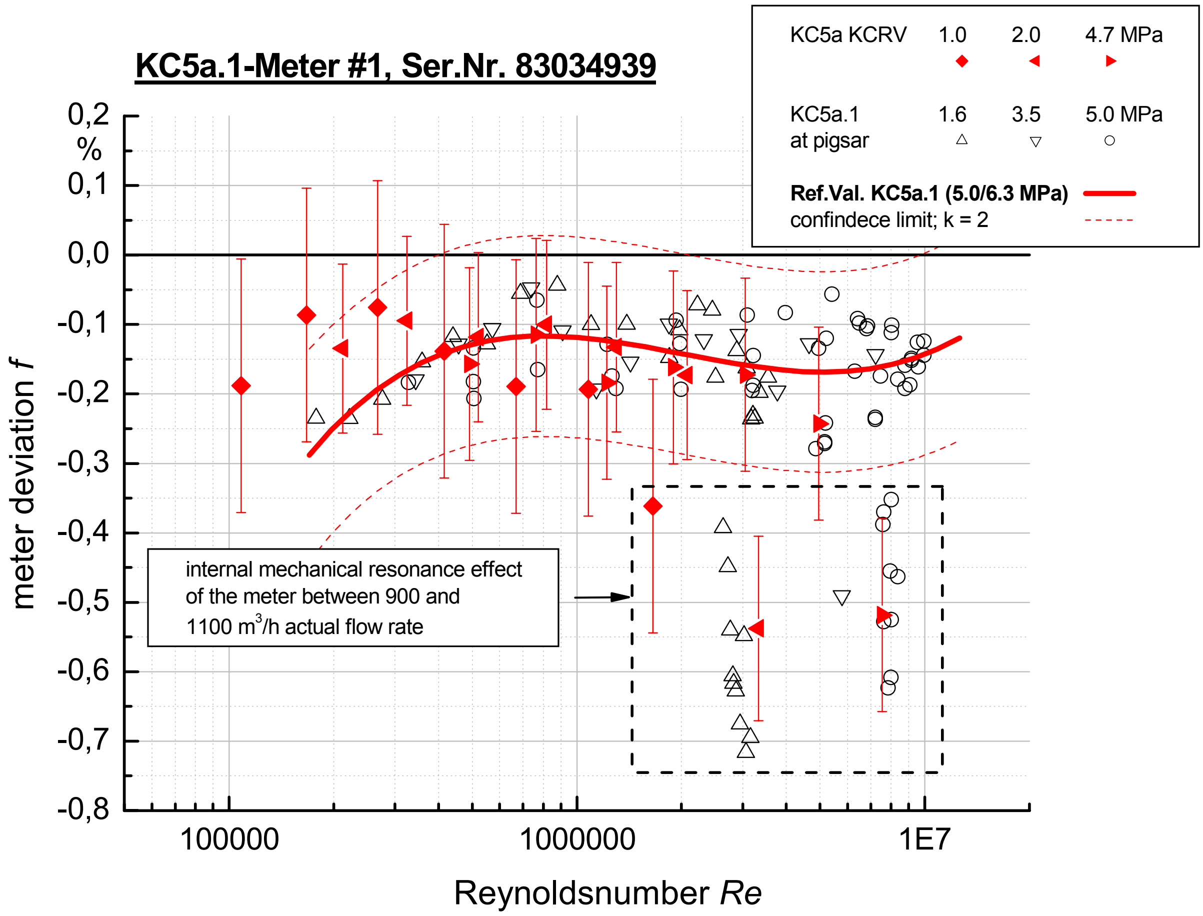

Fig. 3: The measurement results of the K5.a.1-Meter #1 at different pressures within the K5.a and K5.a.1 determined at the pilot laboratory as well as the reference values according to eq. (9) and Tab. 4. See also chapter 3.4 for the behaviour of the meter between 900 and 1100 m^3/h actual flow rate

The red bold line in Fig. 3 presents the CIPM-KCRV as obtained in the previous CCM.FF-K5.a as it is realized at PTB-***pigsar***^{TM}. The outlier at about 1000 m3 / h is due to a resonance effect of the turbine blades and leads to a large scatter.

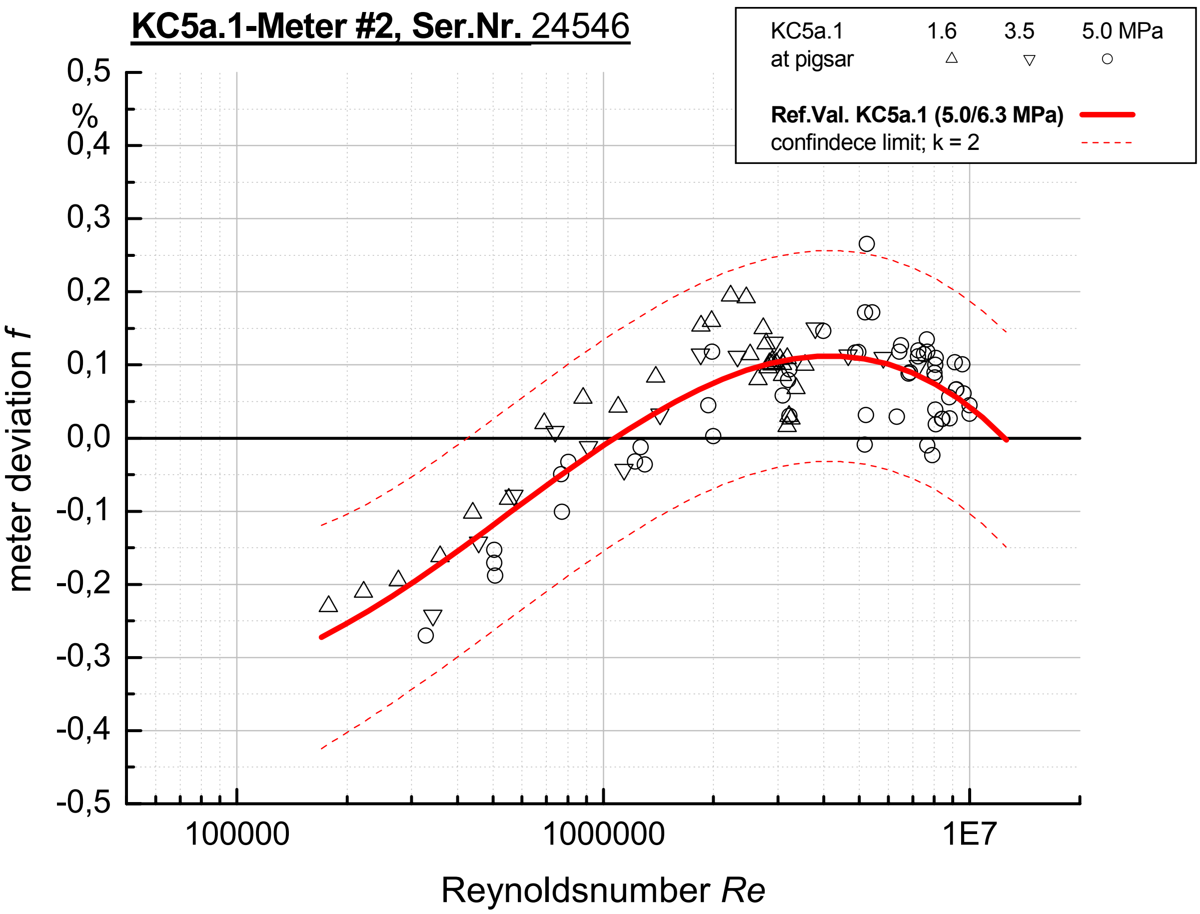

Fig. 4: The measurement results of the K5.a.1-Meter #2 at different pressures within K5.a.1 determined at the pilot laboratory as well as the reference values according to eq. (9) and Tab. 4.

The red bold line in Fig. 4 presents the CIPM-KCRV as obtained in the previous CCM.FF-K5.a and as it is realized at PTB-***pigsar***^{TM}. (same way as in Fig. 3)

As explained in chapter 2.3 above, the single measurement results were used to determine the coefficients in eq. (7) using the Least-Square Approximation-Method. The test of significance for degree of the polynomial shows that a third degree fit is suitable for both meters. Therefore we have finally the function as given by eq. (9) with values for coefficients given in Tab 4:

$$f_{\text{Ref.Val.KC5a.1}} = \sum_{i=0}^{3} a_i \cdot \log^i\left(\frac{\text{Re}}{10^6}\right) \qquad (9)$$

Tab. 4: Coefficients of the polynomials according to eq. (9) representing the Reference Value of K5.a.1 of both meters #1 and #2 of the package

Coefficient	Value for K5.a.1-Meter #1	Value for K5.a.1-Meter #2
a_0	-0.11867	-0,01049
a_1	-0.04056	0.33717
a_2	-0.18414	-0.12583
a_3	0.2005	-0.15832

The Least-Square Approximation results in addition the so called Variance-Covariance_Matrices of the coefficients (see Tab. 5). They are the base to determine the uncertainty of results of eq. (9) or the confidence limit for each Reynolds number used. The formula for the standard uncertainty is given by eq. (10). The resulting polynomials are also plotted in Fig. 3 and 4 including their confidence limits.

Tab. 5: Variance-Covariance-Matrices VCM#1 and VCM#2 of the coefficients of the polynomials according to eq. (9) representing the Reference Value of K5.a.1

	KC5a.1-Meter #1				KC5a.1-Meter #2			
	a_0	a_1	a_2	a_3	a_0	a_1	a_2	a_3
a_0	$5.22\cdot10^{-3}$	$-4.34\cdot10^{-5}$	$-1.51\cdot10^{-4}$	$1.48\cdot10^{-4}$	$5.22\cdot10^{-}3$	$-4.83\cdot10^{-5}$	$-1.51\cdot10^{-4}$	$1.57\cdot10^{-4}$
a_1	$-4.34\cdot10^{-5}$	$3.07\cdot10^{-4}$	$1.34\cdot10^{-4}$	$-4.86\cdot10^{-4}$	$-4.83\cdot10^{-5}$	$2.67\cdot10^{-4}$	$1.25\cdot10^{-4}$	$-4.16\cdot10^{-4}$
a_2	$-1.51\cdot10^{-4}$	$1.34\cdot10^{-4}$	$9.21\cdot10^{-4}$	$-9.43\cdot10^{-4}$	$-1.51\cdot10^{-4}$	$1.25\cdot10^{-4}$	$9.12\cdot10^{-4}$	$-9.32\cdot10^{-4}$
a_3	$1.48\cdot10^{-4}$	$-4.86\cdot10^{-4}$	$-9.43\cdot10^{-4}$	$1.52\cdot10^{-3}$	$1.57\cdot10^{-4}$	$-4.16\cdot10^{-4}$	$-9.32\cdot10^{-4}$	$1.39\cdot10^{-3}$

$$u(f_{\text{Ref.Val.KC5a.1}}) = \mathbf{A} \cdot \mathbf{VCM} \cdot \mathbf{A}^{\mathrm{T}} \quad (k = 1) \qquad (10)$$

were the matrix **A** is the Jacobian Matrix of the polynomials:

$$\mathbf{A} = \begin{pmatrix} \dfrac{\partial f_{\text{Ref.Val.KC5a.1}}}{\partial a_0} & \dfrac{\partial f_{\text{Ref.Val.KC5a.1}}}{\partial a_1} & \dfrac{\partial f_{\text{Ref.Val.KC5a.1}}}{\partial a_2} & \dfrac{\partial f_{\text{Ref.Val.KC5a.1}}}{\partial a_3} \end{pmatrix}$$
$$= \begin{pmatrix} 1 & \log\left(\dfrac{\text{Re}}{10^6}\right) & \log^2\left(\dfrac{\text{Re}}{10^6}\right) & \log^3\left(\dfrac{\text{Re}}{10^6}\right) \end{pmatrix}$$

Looking to the values as obtained from eq. (10), we can find for the expanded uncertainties the following relation:

$$\boldsymbol{U_{\text{KCRV-CCM.FF-KC5a}} < U(f_{\text{Ref.Val.KC5a.1}}) \approx 0{,}145\% < U_{\text{CMC,PTB-pigsar}}} \; (k = 2) \qquad (11)$$

It is very important for the outcome, that the reference values used in this bilateral intercomparison are equivalent to the Key Comparison Reference Value (KCRV) of the previous K5.a. We can demonstrate the equivalence between the KCRV of KC 5.a and the Ref.Val. of K5.a.1 represented by eq. (9) and Tab. 4 using the results of

K5.a.1-Meter #1 as shown in Fig. 3. The values for this proof are given in Tab. 6 for the different flow rates and pressures.

Tab. 6: Comparison of KCRV—K5.a and Ref.Val. -K5.a.1 of K5.a.1-Meter #1(meter deviations); for values of $f_{KCRV\text{-}KC5a}$ and U_{KC5a} see [1]

	p_{KC5a} = 20 MPa						
Q	$f_{\text{KCRV-KC5a}}$	U_{KC5a}	$f_{\text{Ref.Val.KC5a.1}}$	$U_{\text{KC5a.1}}$	$d_{\text{KC5a-KC5a.1}}$	U_{d}	En
[m³/h]	[%]	[%]	[%]	[%]	[%]	[%]	[--]
65	-0.135	0.122	-0.237	0.148	0.102	0.085	1.203
100	-0.095	0.122	-0.167	0.145	0.072	0.079	0.909
160	-0.118	0.122	-0.127	0.145	0.009	0.078	0.112
250	-0.100	0.122	-0.117	0.145	0.016	0.078	0.210
400	-0.133	0.122	-0.125	0.144	-0.007	0.078	0.094
650	-0.173	0.122	-0.144	0.144	-0.029	0.078	0.380
1000	*-0.538*	*0.133*	*-0.161*	*0.144*	*-0.376*	*0.056*	*6.738*
	p_{KC5a} = 47 MPa						
Q	$f_{\text{KCRV-KC5a}}$	U_{KC5a}	$f_{\text{Ref.Val.KC5a.1}}$	$U_{\text{KC5a.1}}$	$d_{\text{KC5a-KC5a.1}}$	U_{d}	En
65	-0.157	0.139	-0.130	0.145	-0.027	0.041	0.668
100	-0.115	0.139	-0.117	0.145	0.002	0.040	0.048
160	-0.184	0.139	-0.123	0.144	-0.061	0.039	1.539
250	-0.162	0.139	-0.140	0.144	-0.022	0.039	0.566
400	-0.172	0.139	-0.159	0.144	-0.014	0.039	0.352
650	-0.243	0.139	-0.168	0.144	-0.075	0.039	1.911
1000	*-0.518*	*0.139*	*-0.160*	*0.144*	*-0.358*	*0.039*	*9.080*
Mean_En (20 and 47 MPa, excluding *Q*= 1000 m³/h)							**0.401**

Please note, that the Mean_En is the geometric average of the En-values for the different flow rates and pressures to express an average En versus the logarithmic scaled flow rate range. This is in accordance to the procedure within the protocol of CCM.FF-K5.a. The arithmetic mean is 0.670.

The flow rate Q = 1000 m^3/h is excluded here for the reason that the meter has a significant deviation from its Reynolds behavior due to internal resonance effects. At this point the polynomial equation eq. (9) does not represent the Ref.Val.K5.a.1 correctly. Please see also chapter 3.4.

For the pressures p_{K5a} = 20 MPa and 47 MPa, the expanded uncertainty of the difference in Tab. 6 between both reference values $U_d = 2\sqrt{u^2_{\text{Ref.Val.KC5a.1}} - u^2_{\text{KCRV-KC5a}}}$ is the most conservative estimation for this uncertainty and includes again the consideration of the covariance of both values in the way as explained in chapter 2.2. It is dominated by the reproducibility and therefore in the order of 0.04% -0.078 %. For the pressure p_{K5a} = 10 MPa, the facility PTB-***pigsar***^{TM} did not contribute to the KCRV-K5.a, therefore we did not consider this range for the demonstration of equivalence.

Looking to the mean En-value =0.4 of Tab. 6 we can conclude

- that the Reference Value for K5.a.1 represented by the eq.(9) and Tab. 4 is equivalent to the KCRV of the K5.a: Ref.Val.K5.a.1 ≡ KCRV-K5.a
- that the Reference Value for K5.a.1 represents therefore the CIPM Key Comparison Reference Value for natural gas under high pressure.

3.3 Reproducibility of the transfer package and the pilot facility

The protocol of the CCM.FF-K5.a [1] and paper [4] describe and apply a method to determine the reproducibility of the transfer meters as well as the test facilities based on the measurements during the period of the KC. This procedure was also successfully applied in the CCM.FF-K5.b for compressed air and nitrogen [5].

Here again we make use of this method to demonstrate the stability of the transfer package and the pilot facility. Using the correlation plot of the single results of both meters in the transfer package with respect to the Reference Value of K5.a.1 (eq. (9) and Tab. 4) one may visualize Fig. 5.

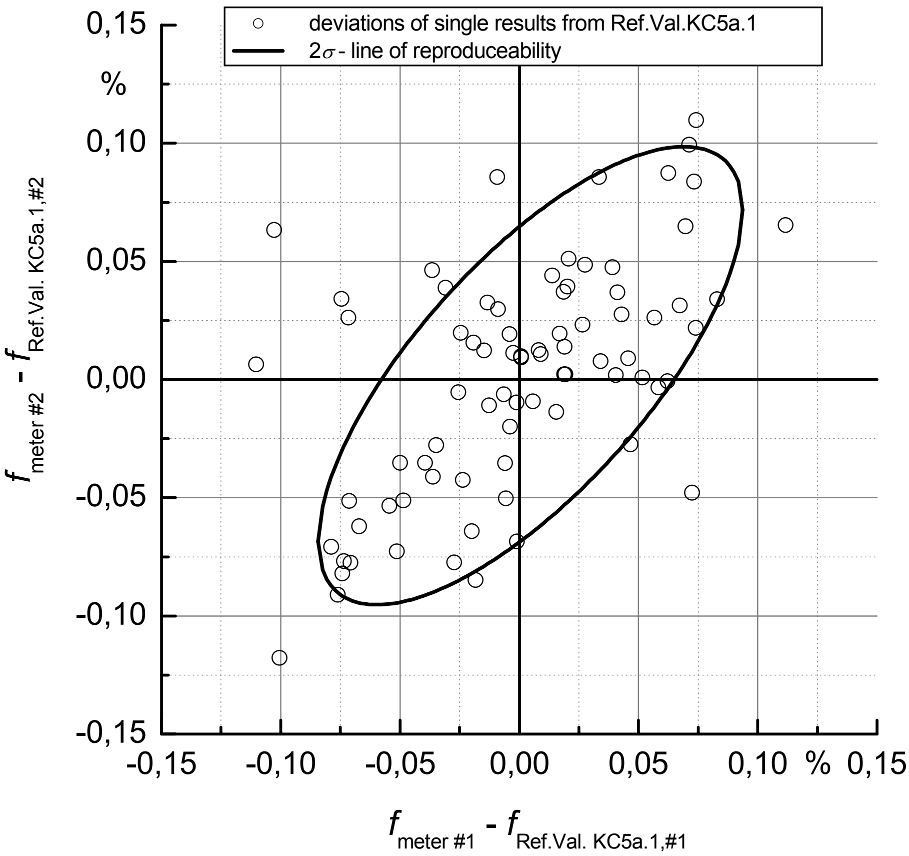

Fig. 5: The correlation plot of the K5.a.1-package within K5.a.1 determined at the pilot laboratory using the deviation between the single measurement results $f_{meter\#i}$ and the reference value $f_{Ref.Val.K5.a.1,\#i}$ according to eq. (9) and Tab. 4.

The values in the Fig. 5 have been evaluated in the same ways as documented in [1] and [5]. We refrain from showing the complete set of equations here again (please see [1]) and give only the results in Tab. 7.

Tab. 7: Tabulated results for overall reproducibility of the transfer package and the pilot lab

	Reproducibility [%]		
Test period	Meter #1 83034949	Meter #2 24546	Pilot lab PTB-***pigsar***^{TM}
CCM.FF-KC5a	$0.050^{+0.009}_{-0.007}$	--	$0.070^{+0.013}_{-0.010}$
CCM.FF-KC5a.1	$0.041^{+0.008}_{-0.006}$	$0.056^{+0.011}_{-0.008}$	$0.079^{+0.015}_{-0.011}$

Please read e.g $0.050^{+0.009}_{-0.007}$ as 0.050 for the estimated value and 0.050-0.007 = 0.043 for the lower confidence level as well as 0.050+0.009 = 0.059 for the upper confidence level (k = 2).

Tab. 7 presents in addition the results out of CCM.FF-K5.a (for K5.a.1-Meter#1 and the pilot lab) to demonstrate the equivalence of the results in both KCs. Please note, that the reproducibility of the pilot lab in CCM.FF-K5.b [5] was determined also to be $0.077^{+0.014}_{-0.010}$.

3.4 Note on behavior of Meter #1 at 1000 m^3/h

During the enhanced testing of K5.a.1-Meter #1 used for this intercomparison it turned out that we have to consider a special behavior of this meter at flow rates very close to Q = 1000 m^3/h. At this flow rate the meter shows an internal resonance effect and does not follow its Reynolds balanced behavior as at other flow rates. This is easily to be seen, when the meter deviations are plotted versus the flow rate as shown in Fig. 6.

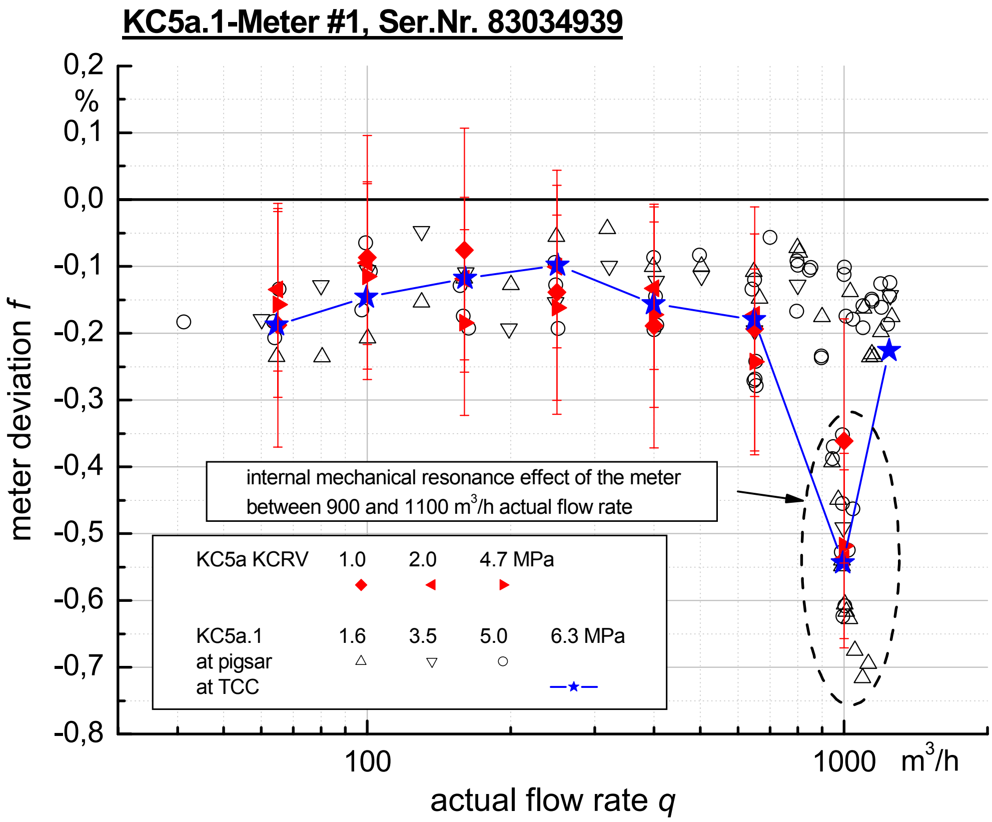

Fig. 6: The measurement results of the K5.a.1-Meter #1 at different pressures plotted versus the flow rate. The meter has a significant resonance effect between 900 and 1100 m3/h actual flow rate which is not very stable. Therefore it was decided to exclude the flow rate 1000 m^3/h from the evaluation for this meter and to expand the flow rate to the point 1250 m^3/h.

Unfortunately, the effect at Q = 1000 m^3/h is not as stable as the values at other flow rates and shows significant higher scatter. In principle, the effect can be described by an additional term in eq. (9) in the form of $\dfrac{k_1}{(Q - Q_{resonance})^2 + k_2}$ (resonance curve versus flow rate), but this makes the evaluation much more complicated, difficult to be understood and not more reliable.

As an alternative, we decided to expand the flow rate range used in his intercomparison up to the flow rate Q_{max} = 1250 m^3/h. This load of 125% of nominal maximum flow rate of the meters is not detrimental for meters of this technology. At Q_{max} = 1250 m^3/h meter #1 again shows good Reynolds balanced behavior as expressed by eq. (9) and Tab. 4.

4 K5.A.1: GRAPHS AND TABLES OF THE RESULTS

4.1 Calibration at NRC-TCC with 6.3 MPa compared to Ref.Val.K5.a.1

The bold red line in Fig. 7 and 8 present the CIPM KCRVs as realized at PTB-***pigsar***^{TM} for meter #1 as well as meter #2. The blue stars present the calibration NRC-TCC.

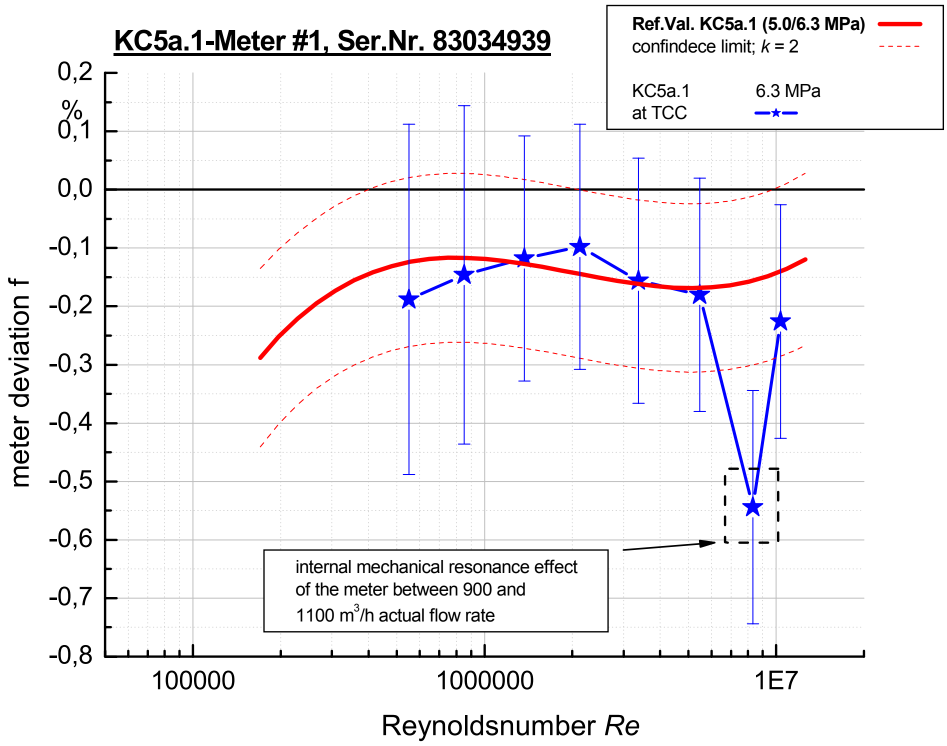

Fig. 7: The results of measurements for K5.a.1-Meter #1 at TCC versus Reynolds number. For Ref.Val. K5.a.1 see also eq.(9) and Tab. 4.

It can bee seen immediately that NRC-TCC is in excellent agreement with the European Harmonized Reference Values (EHRV).

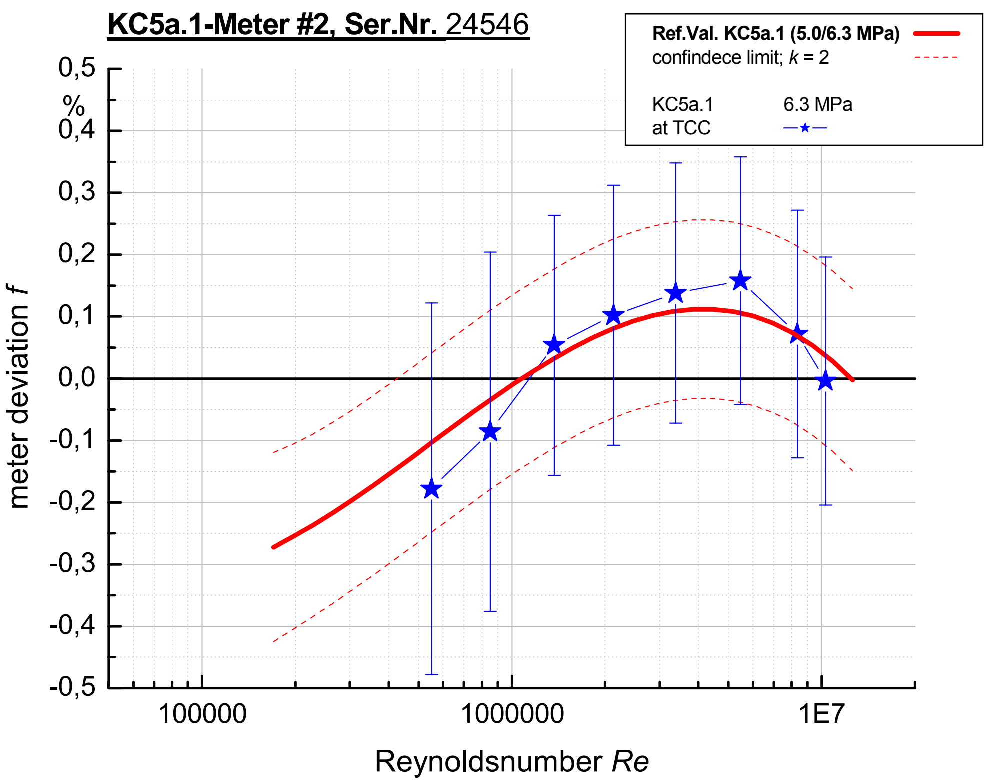

Fig. 8: Results of measurements for K5.a.1-Meter #2 at TCC versus Reynolds number. For Ref.Val. K5.a.1 see also eq.(9) and Tab. 4.

4.2 Difference to the BIPM Reference Value

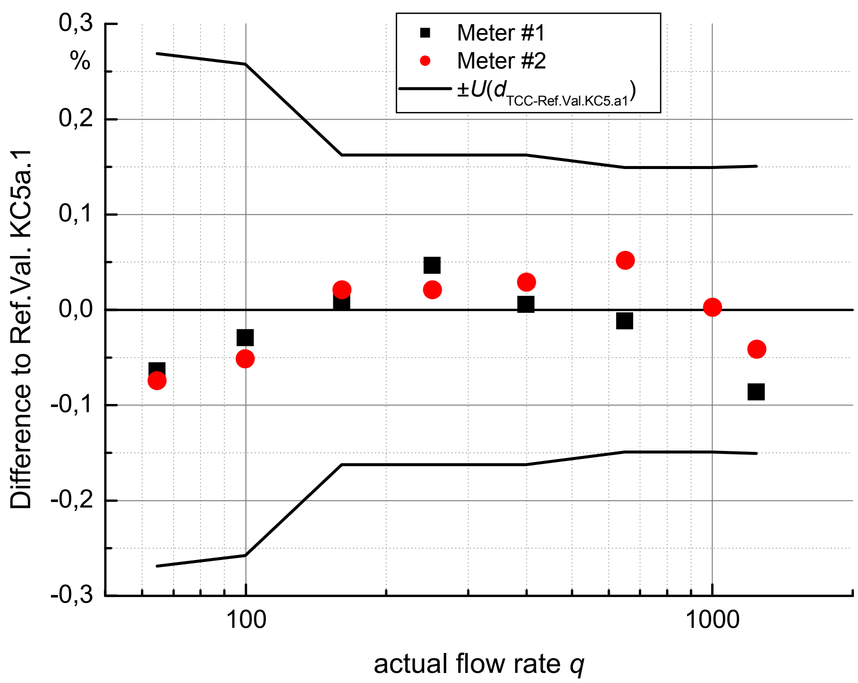

Fig. 9: The differences of the results of NRC-TCC to the Ref.Val K5.a.1 (see also Tab. 4 and eq. (9)) in comparison to the uncertainty level of the difference determined according to eq. (6).

The bold upper and lower uncertainty limits are given by the following equation (12)

$$u\left(d_i\right)=\sqrt{u_{\mathrm{pigsar}}^2+u_{\mathrm{TCC}}^2-2u_{\mathrm{KCRV-KC5a}}^2} \tag{12}$$

and describes the extreme limits of the maximal allowed limits of deviation. Any deviation beyond these limits is a significant one.

4.3 Comparison of En with the CIPM Reference Value

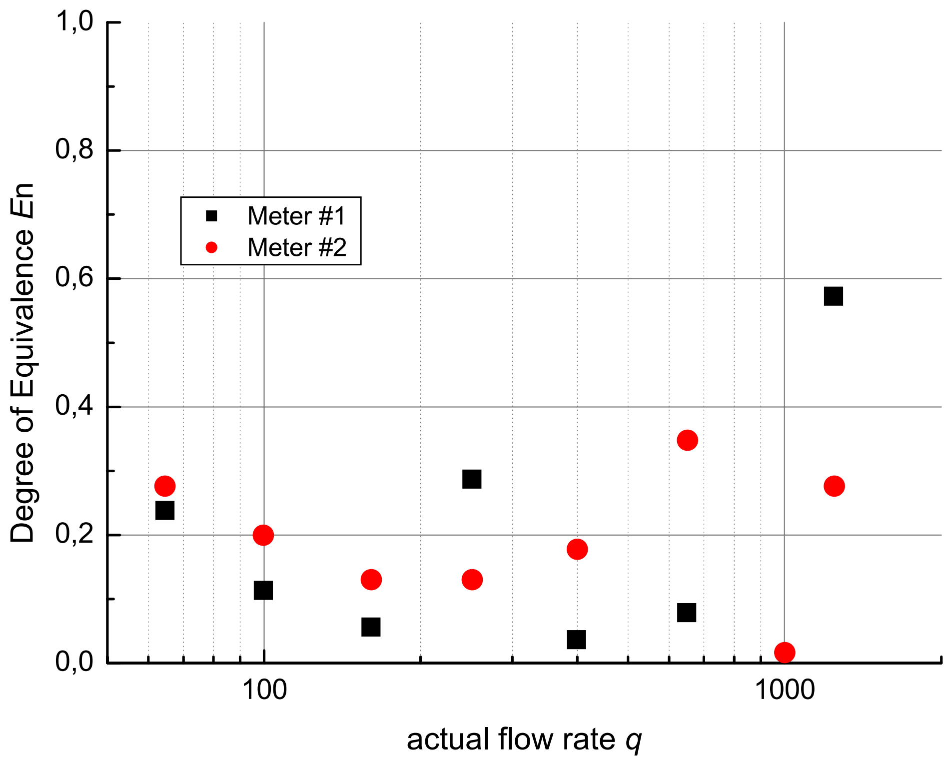

Fig. 10: The Degree of Equivalence of the results of NRC-TCC with ***pigsar***$^{\mathrm{TM}}$ *[see eq. (2) and (6)].*

Accordingly to the definition of En in equation (2), En=0 means total agreement with the European Harmonized Reference Value (EHRV). En=1 means that the error bars of the facility just overlap with the uncertainty bars of the EHRV.
In the case of NRC-TCC the degree of equivalence with the EHRC (or CIPM KCRV) is extremely good in the entire flow rate range. .

4.4 Tabulation of results: lab-to-KCRV and En for TCC

Tab 8: Measurement results of TCC, the reference values of K5.a.1 acc. to eq. (9) and Tab. 4 and the corresponding expanded uncertainties (k = 2) as well as the Degrees of Equivalence En using the K5.a.1-Meter#1, Ser. Nr. 83034949

Date of Measurement: Oct 2006

Q [m^3/h]	Re --	f_{TCC} [%]	$U(f_{TCC})$ [%]	$f_{Ref.Val.KC5a.1}$ [%] (eq. 9)	$U(f_{Ref.Val.KC5a.1})$ [%] (eq. 10)	$U(_{KCRV-KC5a})$ [%] [1]	$d_{TCC-Ref.Val.KC5a.1}$ [%] (eq. 8)	$U(d_{TCC-Ref.Val.KC5a.1})$ [%] (eq. 6)	**En --**
64.55	5.506E+05	-0.188	0.300	-0.124	0.145	0.139	-0.064	0.269	**0.238**
99.67	8.512E+05	-0.146	0.290	-0.117	0.145	0.139	-0.029	0.258	**0.113**
160.59	1.369E+06	-0.118	0.210	-0.127	0.144	0.139	0.009	0.162	**0.056**
250.81	2.124E+06	-0.098	0.210	-0.145	0.144	0.139	0.047	0.162	**0.287**
398.86	3.370E+06	-0.156	0.210	-0.162	0.144	0.139	0.006	0.162	**0.036**
648.85	5.463E+06	-0.180	0.200	-0.168	0.144	0.139	-0.012	0.149	**0.078**
994.91	8.328E+06	--	--	--	--	--	--	--	**--**
1243.42	1.035E+07	-0.226	0.200	-0.140	0.146	0.139	-0.086	0.150	**0.572**
								Mean_En	**0.132**

Tab 9: Measurement results of TCC, the reference values of K5.a.1 acc. to eq. (9) and Tab. 4 and the corresponding expanded uncertainties (k = 2) as well as the Degrees of Equivalence En using the K5.a.1-Meter#2, Ser. Nr. 24546

Date of Measurement: Oct 2006

Q [m^3/h]	Re --	f_{TCC} [%]	$U(f_{TCC})$ [%]	$f_{Ref.Val.KC5a.1}$ [%] (eq. 9)	$U(f_{Ref.Val.KC5a.1})$ [%] (eq. 10)	$U(_{KCRV-KC5a})$ [%] [1]	$d_{TCC-Ref.Val.KC5a.1}$ [%] (eq. 8)	$U(d_{TCC-Ref.Val.KC5a.1})$ [%] (eq. 6)	**En --**
64.56	5.502E+05	-0.178	0.300	-0.104	0.145	0.139	-0.074	0.269	0.276
99.73	8.514E+05	-0.086	0.290	-0.035	0.145	0.139	-0.051	0.258	0.199
160.81	1.371E+06	0.054	0.210	0.033	0.144	0.139	0.021	0.162	0.130
251.31	2.127E+06	0.102	0.210	0.081	0.144	0.139	0.021	0.162	0.130
400.04	3.378E+06	0.138	0.210	0.109	0.144	0.139	0.029	0.162	0.178
651.05	5.471E+06	0.158	0.200	0.106	0.144	0.139	0.052	0.149	0.348
1001.06	8.341E+06	0.072	0.200	0.069	0.144	0.139	0.002	0.149	0.016
1246.17	1.030E+07	-0.004	0.200	0.037	0.145	0.139	-0.041	0.150	0.276
								Mean_En	**0.150**

Please note, that the Mean_En is the geometric average of the En-values for the different flow rates to express an average value for the En versus the logarithmic scaled flow rate range. This is in accordance to the procedure within the protocol of CCM.FF-K5.a.

5 SUMMARY, FINAL REMARKS

The test facilities NRC-TCC and PTB-***pigsar***^{TM} provide equivalent calibration results based on their claimed calibration and measuring capabilities (CMC).

The tests at the pilot laboratory assure that the reference values used in this work, K5.a.1, are fully equivalent to the KCRV of the previous CIPM Key Comparison CCM.FF-K5.a for natural gas under high pressure [1].

Therefore this key comparison, CCM.FF-K5.a.1, documents the equivalence of the measurement (calibration) results of NRC-TCC with the CIPM KCRV.

The Degree of Equivalence between the results of both facilities, NRC-TCC and PTB-***pigsar***^{TM} are excellent and the En values have been demonstrated to be much smaller than 1.0.

Due to the common traceability of both test facilities to the CIPM Key Comparison Reference Value of CCM.FF-K5.a [1], the evaluation of the results within this intercomparison had to consider the correlation of the measurement results. The procedure has been explained and was done carefully using the most conservative estimation for the value of covariance between the results.

The criteria of equivalence in such a case among correlated facilities are significantly tightened compared to independent facilities with the same claimed uncertainties. Therefore the very low En values, less than 0.15 (in average) has to be emphasized. Similarly, the degree of equivalence between the two participants is excellent. This is a clear proof not only of the capabilities of NRC-TCC but also of the reliability of the harmonization process between LNE, NMi-VSL and PTB (documented in [1], annex 9) as well as the efficacy of the subsequent calibration process of NRC-TCC performed by NMi-VSL.

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