Bilateral inter comparison FORCE – PTB

EURAMET.M.FF-K5a

EURAMET-Project E1111
Follow up to CCM.FF-KC5a
Volume flow rate for Natural Gas und High Pressure

- **Pilot laboratory:**
  PTB
  *contact: B. Mickan, H. Toebben, (PTB-**pigsar**TM), Bodo.Mickan@ptb.de,*

- **Participating Laboratory:**
  FORCE Technology Navervej 1 6600 Vejen, Denmark.
  contact: Jesper Busk. jrb@force.dk

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1 INTRODUCTION

2 THE PRINCIPLES OF THIS INTERCOMPARISON

2.1 The situation of the traceability chains

The PTB operates at the test facility PIGSAR an High Pressure Piston Prover as a primary reference device to trace back the gas measurement down to the SI-Units.

FORCE Technology is the National Metrology Institute in Denmark for gas flow measurement, and operates the low pressure and high pressure calibration test facility for calibration purpose in Denmark.

It has been decided by the staff of FORCE to get their traceability from the PTB (Germany). Hence, the test facility of FORCE traces back directly to the KCRV of CCM.KC-FF 5a.

Without an independent traceability at FORCE, the actual inter comparison (EURAMET.M.FF-K5a) will not establish a new KCRV but will proof the consistency of FORCE calibrations with the existing KCRV of KC-FF 5a. For the evaluation of the inter-comparison results it is necessary to consider the dependence (correlation or covariance rsp.) of both participant PTB-PIGSAR and FORCE due to their common reference (the KCRV of CCM.FF-KC5a). This is explained in the following chapter 2.2.

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

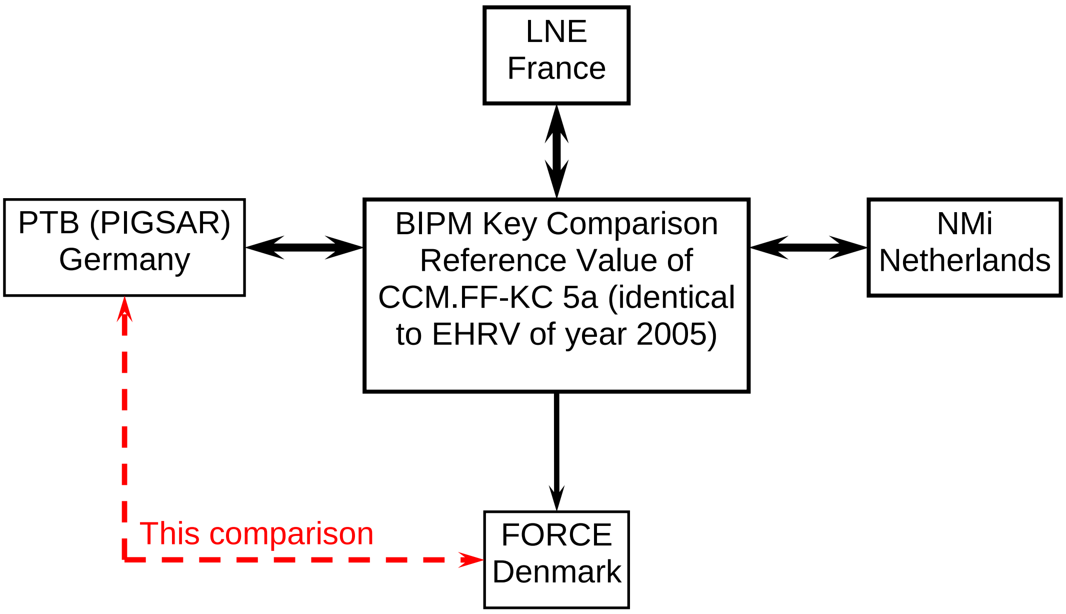

Fig. 1: The traceability of the participants in relation to the BIPM Reference Value of CCM.FF-KC5a and the position of this bilateral inter comparison

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

In any key comparison, the differences between the participating laboratories and the key comparison reference value KCRV have to be calculated according to

$$d_i = x_i - x_{KCRV} \qquad (1)$$

Based on these differences, the **D**egree **o**f **E**quivalence (DoE) shall be calculated according to:

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

were $U(d_i)$ is the expanded uncertainty (k = 2) of the difference d_i.

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

- The results of a laboratory are ***equivalent (passed) if 1 < E_i***.

- The laboratory was determined as ***not equivalent (failed) if E_i or E_{ij} >1.2***.

- For values of DoE in the range ***1 < E_i or E_{ij} ≤ 1.2*** we define “**warning** level” were actions to check is recommended to the laboratory.
  The reason for such “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 inter comparisons 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 inter comparisons 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 needs the information about the uncertainty of the differences d_i acc. 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:

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

In the case of this inter comparison, the results of the participants are correlated duo to the common traceability. The correlation leads to a significant covariance *cov* between the measurement results which has to be considered in the eq. (3).

The worst case estimation for the covariance which can occur due to the common traceability is the squared uncertainty of this common reference. In our case it is the uncertainty of the key comparison reference value of CCM.FF-K5a (see also Fig. 1). The value for the expanded uncertainty of the KCRV was determined between 0.12% and 0.138% depending on flow rate and pressure. **We assume an upper value of 0.14% and make with this sure that no underestimation of the degree of equivalence has been done.**

2.3 The basic principles for the linking of the results of CCM.FF-K5a with this inter comparison

The key comparisons for high pressure gas organized up to now have all the same common concept for the measurand. Even the basic mathematical relations are simple, we like to explain here something in detail to avoid any confusion or misunderstanding, especially where we have to link different inter comparison round by different meters under test.

The central expression used to quantify the meter under test in relation to the fluid quantity is the relative deviation of the indicated quantity[1] Q_{MuT} to the reference quantity $Q_{Lab\#i}$ provided by the Lab #i for the measurement (meter deviation f_i).

$$f_i = \frac{Q_{MuT}}{Q_{Lab\#i}} - 1 \tag{1}$$

Based on all results for the meter deviation at the different laboratories the key comparisons reference value f_{KCRV} was calculated as a weighted mean (w_i is the weight for Lab #i).

$$f_{KCRV} = \sum w_i \cdot f_i = \frac{Q_{MuT}}{Q_{KCRV}} - 1 \tag{2}$$

The key reference value for the meter deviation can also be formally expressed as a relative deviation of the meter indication to the key reference quantity.

To express the degree of equivalence the difference d_i (and its accompanied uncertainty) between the measured value f_i at Lab #i and the key reference value f_{KCRV} is calculated:

$$d_i = f_i - f_{KCRV} \tag{3}$$

The interest is finally the relative deviation $\Delta Q_{\#i,rel}$ of the quantity $Q_{Lab\#i}$ to the key reference quantity Q_{KCRV}:

$$\Delta Q_{\#i,rel} = \frac{Q_{Lab\#i}}{Q_{KCRV}} - 1. \tag{4}$$

The relation ship of this to the usually used difference d_i (3) shall be shown here. Even this was the common understanding among the flow experts it was never expressed in detail in the CCM.FF-protocols up to now.

The relation is easily shown if we expand the expression (4) by an unity Q_{MuT}/Q_{MuT}. Furthermore we make use of (1) and (2) as well as some small approximation due to the fact that f_i as well as f_{KCRV} are much smaller than 1.[2] The final outcome is that the usual used value d_i is the negative value of the original interest $\Delta Q_{\#i,rel}$.

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[1] Please note the here the quantity can be volume, mass, volume flow rate or mass flow rate according to the indication of the meter under test. The meter under tests in the CCM.FF-KC5 are turbine meters.

[2] E.g. if the deviations f are in the order of 0.5%, the final error of the approximations used in (5) can reach ±0.005% in maximum. This is of course an additional uncertainty which has to be considered but in the field of high pressure gas measurement definitely insignificant compared to the CMC uncertainties.

$$\Delta Q_{\#i,rel} = \frac{Q_{Lab\#i}}{Q_{MuT}} \cdot \frac{Q_{MuT}}{Q_{KCRV}} - 1 = \frac{1+f_{KCRV}}{1+f_i} - 1 \approx (1+f_{KCRV}) \cdot (1-f_i) \approx f_{KCRV} - f_i = -d_i \quad (5)$$

The expansion by Q_{MuT}/Q_{MuT} in (5) is made on the background that the dependency of the meter deviation *f* on the fluid quantity *Q* is normally negligible small at least for small changes of quantity.[3]. It has to emphasized here that the expansion is independent to a special value of Q_{MuT} and therefore also independent to the meter under test. This means the independence of the $\Delta Q_{\#i,rel}$ to the meter under test used for comparison which was utilized in the past CCM.FF-KCs (1 to 6 except 4) by silent agreement of the flow experts. Within the comparison rounds the results coming from at least two different meters under test were combined (in case of CCM.FF-KC6 even results of 4 meters under test were summarized).

The next step are considerations about the differences $d_{i,j}$ between to laboratories Lab #i and Lab #j determined in a comparison. We make use of the same approach as above to transform the relative deviation of the quantities to the difference of the meter deviations determined in the comparison:

$$d_{i,j} = \frac{Q_{Lab\#i}}{Q_{Lab\#j}} - 1 = \frac{Q_{Lab\#j}}{Q_{MuT}} \cdot \frac{Q_{MuT}}{Q_{Lab\#j}} - 1 = \frac{1+f_i}{1+f_j} - 1 \approx f_i - f_j \quad (6)$$

This comparison documented in this protocol is an subsequent comparison (SC) to the CCM.FF-KC5a. Hence, we have to look careful to the time order of values which we put into our calculations when we want to determine finally the difference (degree of equivalence) d_{FORCE} of the Lab #*PTB* to the KCRV of the previous key comparison [1] indirect via the Lab #*PTB* using the difference $d_{PTB,FORCE}$. The brackets $\langle \; \rangle$ with the indices “KC” and “SC” indicates values determined in the key comparison and the subsequent comparison:

$$\langle d_{FORCE,PTB} \rangle_{SC} = \langle f_{FORCE} \rangle_{SC} - \langle f_{PTB} \rangle_{SC} = \langle f_{FORCE} \rangle_{SC} - \langle f_{PTB} \rangle_{KC} - \Delta_{PTB} \quad (7)$$

$$\text{with } \Delta_{PTB} = \langle f_{PTB} \rangle_{SC} - \langle f_{PTB} \rangle_{KC}$$

With this we get our final expression (8) for the difference of the Lab #*FORCE* to the KCRV of the previous KC:

$$d_{NIST} = \langle f_{FORCE} \rangle_{SC} - f_{KCRV} = \langle d_{PTB} \rangle_{KC} + \Delta_{PTB} + \langle d_{FORCE,PTB} \rangle_{SC} \approx -\left(\frac{Q_{lab\#FORCE}}{Q_{KCRV}} - 1 \right) \quad (8)$$

$\langle d_{PTB} \rangle_{KC}$ is documented in the protocol of the previous KC [1] and is summarized in chapter 3.3.3 . The value Δ_{PTB} is assumed normally as zero with an uncertainty which is the reproducibility of the Lab #*PTB* (stability versus time). In the special case of this subsequent comparison it is known that Δ_{PTB} is different from zero due to the complete new recalibration of the test facility *pigsar* [4] in 2007 and the new cycle within the European Harmonization Group starting 2008 (were also all other partners [LNE, VSL] recalibrate their facilities before). Therefore it is determined an estimator

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[3] This assumption is of course not exactly fulfilled and leads again to additional uncertainties. If these uncertainties are not acceptable , the next level can be the expression the dependency of *f* to *Q* by an appropriate analytical function to apply an small correction (as it was done e.g. in the CCM.FF-KC6) to reduce these additional uncertainties.

in chapter 3.3.2 for this Δ_{PTB} based on the measurements of four measurement series at *pigsar* in years 2004 and 2005 (harmonization cycle 2004-2007) and in the year 2009 (harmonization cycle 2008-2011).

All components in equation (8) have contributions to the total uncertainty of the final value d_{NIST}. They are determined and documented in chapter 3.3 and 4 in this protocol.

3 THE TRANSFER PACKAGE AND TEST PROGRAM

3.1 The meters (technical description)

The transfer package is identical to the package which was used in the CCM.KC5a.1

- Two turbine meters in series
- Size of meter: DN150 (6"), Q_{max} = 1000 m^3/h
- Each turbine meter is equipped with inlet pipe of 1,5 m (10D) length, flow conditioner at the entrance of piping and outlet pipe of 0,45m (3D) length.
- Manufacturer: Meter #1 by Elster-Instromet; Meter #2 by RMG
- Both meters are Reynolds balanced in a wide range

3.2 The measurement program and the calibration of transfer package with the BIPM Reference Value (Equivalence between KCRV-KC5a and Ref.Val.KC5a.1)

Tab. 2: Flow rates and pressures used within the key comparison CCM.FF-KC5a.1

Flow rate [m^3/h] (actual conditions)	PTB	pressure [MPa]	Force	pressure [MPa]
	1.6	5.0	1.6	5.0
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

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

CCM.FF-KC.5a.2	**1.6**	**5.0**
KC5a.2 - PTB #1	March 2009	March 2009
KC5a.2 - **FORCE**	August 2009	August 2009
KC5a.2 - PTB #5	September 2009	September 2009

3.3 Reproducibility of the transfer package and the pilot facility as well as link to the KCRV of CCM.FF-KC5a

Here the results of investigation about stability of the transfer package as well as the pilot lab will be placed. The investigation will be based on the measurement results gathered within this inter comparison as well as on the calibrations results of artefacts of CCM.FF-KC5a.1 [5]. The evaluation will be performed in similar way as for all the CCM.FF-KC5.

The information about reproducibility will also be used for the linking to the KCRV of CCM.FF-KC5a and to determine a degree of equivalence in relation to this KCRV.

3.3.1 Reproducibility

The protocol of the CCM.FF-KC5a [1] 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-KC5b for compressed air and nitrogen [6].

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 differences of single measurement results with respect to the least square fit of all test results (i.e. the residuals) for both meters in the transfer package one obtain to the visualization of Fig. 5. The scatter of the residuals indicates the reproducibility of the measurements and can be split by analysis into the components of both meters and the reference standard.

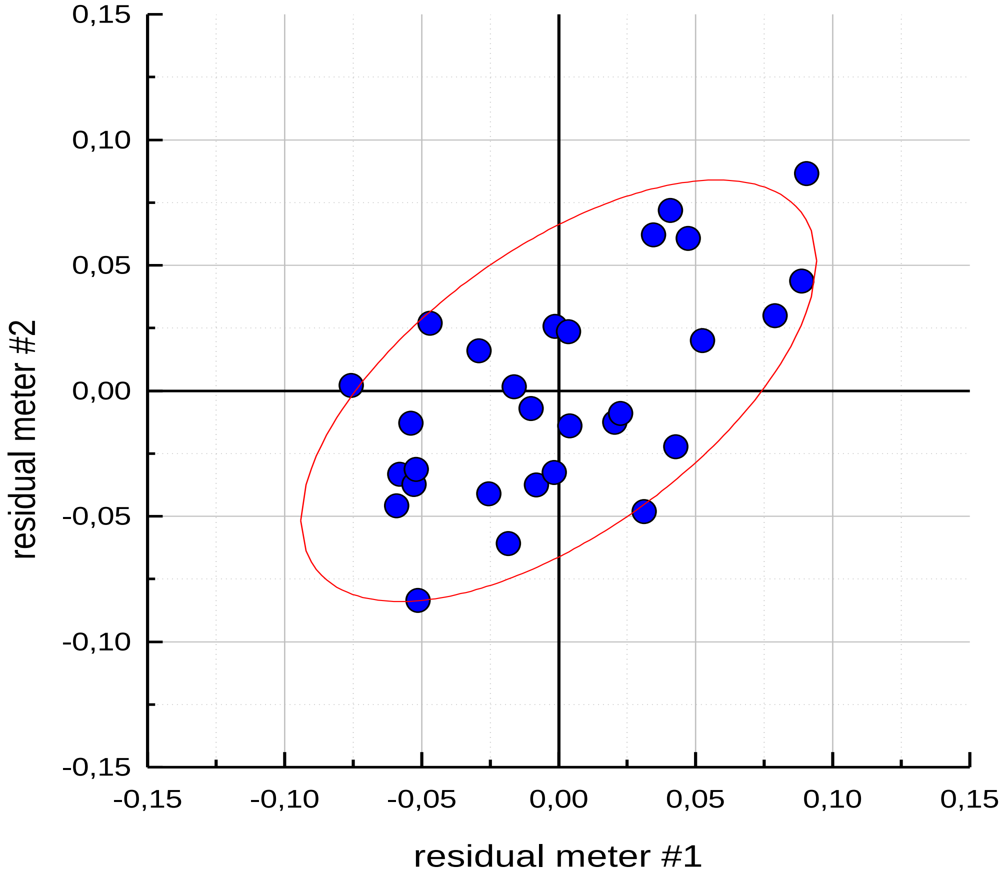


Fig. 3.1: The correlation plot of two meters within EURAMET.M.FF-K5a determined at the pilot laboratory using the difference (residuals) between the single measurement results $f_{meter\#i}$ and the average value $f_{ave\#i}$ (least square fit of test result measured at 1600 kPa and 5000 kPa in March and September 2009).

The values in the Fig. 5 have been evaluated in the same ways as documented in [1]. We refrain from showing the complete set of equations here again (please see [1]) and give only the results in Tab. 3.4.

Tab. 3.4: Tabulated results for reproducibility U_{repro} (k = 2) of the transfer meters *and the pilot lab in all comparison loops related to CCM.FF-K5*

	Reproducibility				
Package pipe size	150 mm		300 mm		
Test period	Meter #1 83034949	Meter #2 24546	Meter #1 74174	Meter #2 2740	Pilot lab *pigsar*
CCM.FF-K5a	$0{,}050^{+0{,}009}_{-0{,}007}$	--	--	--	$0{,}070^{+0{,}013}_{-0{,}010}$
CCM.FF-K5a.1	$0{,}038^{+0{,}007}_{-0{,}005}$	$0{,}058^{+0{,}011}_{-0{,}008}$	--	--	$0{,}077^{+0{,}015}_{-0{,}011}$
CCM.FF-K5a.2	**--**	**--**	$0{,}031^{+0{,}010}_{-0{,}006}$	$0{,}044^{+0{,}014}_{-0{,}008}$	$0{,}062^{+0{,}019}_{-0{,}012}$
EURAMET.M.FF-K5.a	$0{,}064^{+0{,}021}_{-0{,}013}$	$0{,}048^{+0{,}015}_{-0{,}009}$	--	--	$0{,}071^{+0{,}023}_{-0{,}014}$

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. 3.4 presents in addition the results out of the CCM.FF-K5a, K5a.1-Meter and EURAMET.M.FF-K5.a to demonstrate the equivalence of the results in all KC loops.

3.3.2 Shift in the calibration value at pigsar

The complete new recalibration of the test facility *pigsar* [4] in 2007 and the new cycle within the European Harmonization Group starting 2008 (were also all other partners [LNE, VSL] recalibrate their facilities before) defined a new calibration value at the test facility PTB-*pigsar* compared to the situation in 2005 (when the actual KCRV of CCM.FF-k5a was determined). For the linkage between the test result of NIST and the KCRV we need information about the shift $\Delta_{PTB} = \langle f_{PTB} \rangle_{SC} - \langle f_{PTB} \rangle_{KC}$ (see also chapter 2.2) between 2009 and 2004. For the determination of this value we made use of following sets of data measured at pigsar before and after recalibration:

- of both meters used in CCM.FF-K5a.2
- of both meters used in EURAMET.M.FF-K5a
- all meters used inside harmonisation between PTB, LNE and VSL
- all working standards of PTB-pigsar

The shifts for the different sets of meters you can find in Fig. 3.2 below.

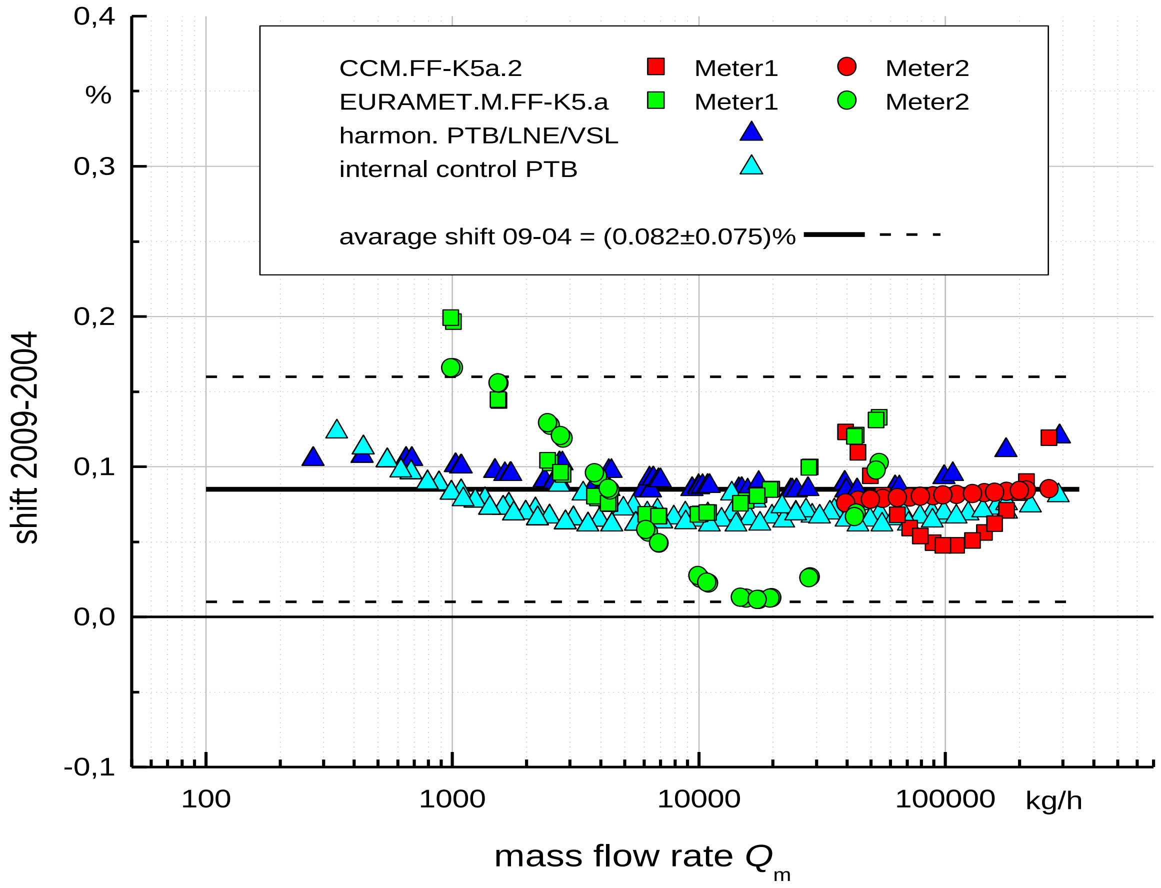


Fig. 3.2: Shift in the calibration values for meters under test at PTB-pigsar due to recalibration 2007 for different sets of meters.
The shift is plotted versus the mass flow rate Q_m because the Reynolds number not comparable due to different pipe sizes of the meters (100 mm to 400 mm)

Finally we found an average shift of **Δ_{PTB} = 0.082 ±0.075 %** were the uncertainty of 0.075% for this value is in good agreement with the reproducibility documented in table 3.4 above.

3.3.3 Value of difference $\langle d_{PTB} \rangle_{KC}$ of PTB the KCRV in CCM.FF-K5a

The values for $\langle d_{PTB} \rangle_{KC}$ in CCM.FF-K5a were determined in a range of mass flow rate between 1040 and 37600 kg/h as shown in Fig. 3.3. The uncertainty of $\langle d_{PTB} \rangle_{KC}$ ranges from 0.08% to 0.10%.

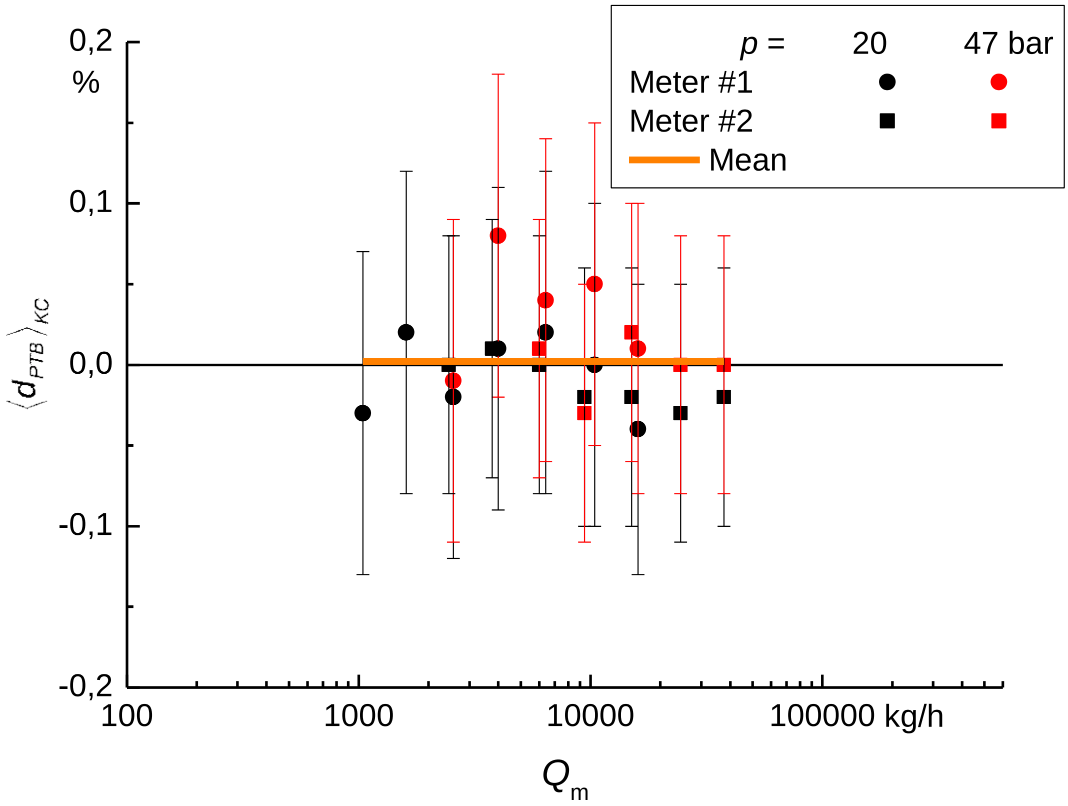
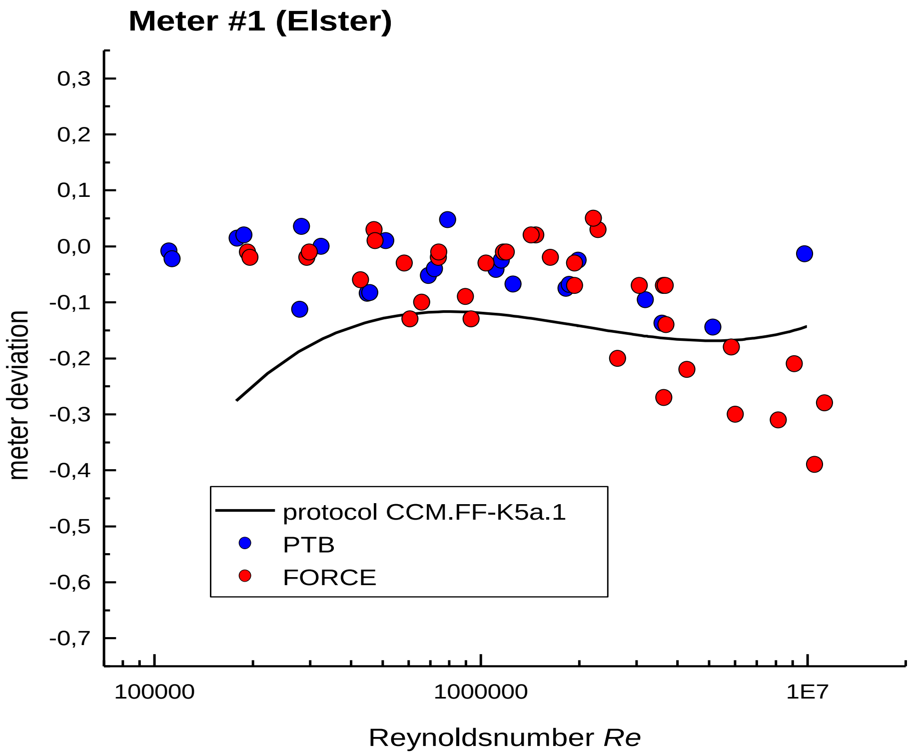
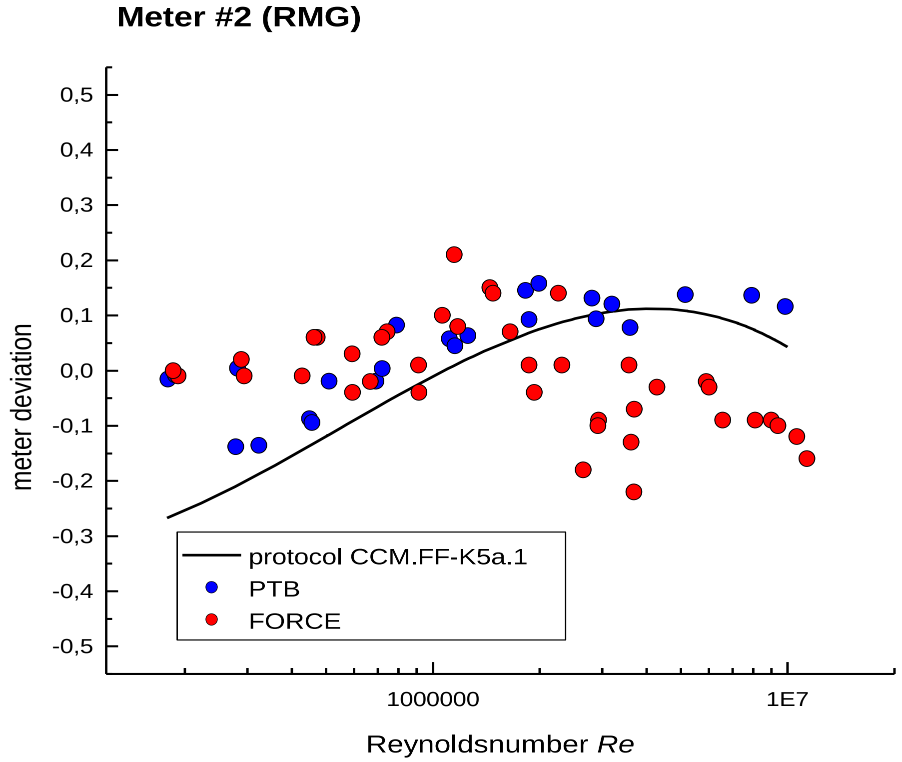


Fig. 3.3: Results for the difference of PTB $\langle d_{PTB} \rangle_{KC}$ to the KCRV in the CCM.FF-K5a.

4 THE TEST RESULTS





The difference for the bilateral comparison of FORCE-PTB is calculated acc.:
$d_{FORCE\text{-}PTB} = f_{FORCE} - f_{PTB}$
what leads consequently for the expanded uncertainty
$U(d_{FORCE\text{-}PTB}) = [U^2(f_{FORCE})+U^2(f_{PTB})]^{0.5}$;

The difference of FORCE to the KCRV of CCM.FF-K5a is calculated acc. eq. (8):

$$d_{FORCE} = \langle f_{FORCE} \rangle_{SC} - f_{KCRV} = \langle d_{PTB} \rangle_{KC} + \Delta_{PTB} + \langle d_{FORCE,PTB} \rangle_{SC} \qquad (8)$$

with

$U(d_{FORCE}) = [U^2(d_{PTB,CCM.FF\text{-}K5a})+U^2(\Delta_{PTB}) +U^2(d_{FORCE\text{-}PTB})\text{-}2*\mathrm{cov}]^{0.5}$;

were cov is the squared uncertainty of the common source of traceability estimated with (0.14%)^2 as mentioned above in chapter 2.2.

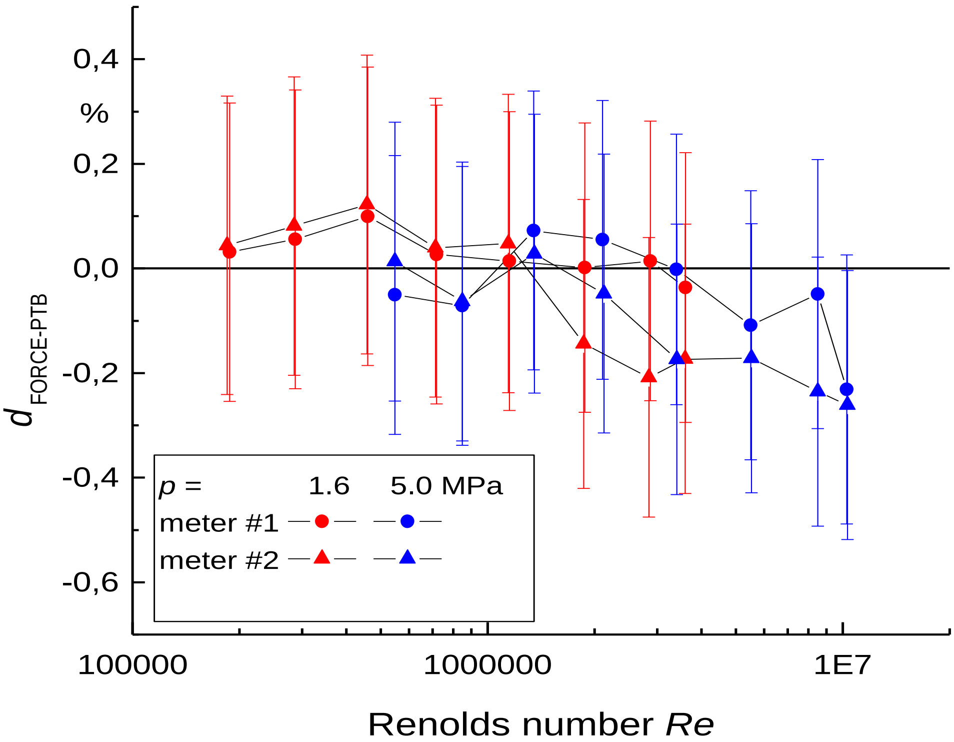


Fig. 4.3: Plot of bilateral differences NIST-PTB versus Reynolds number Re both meters;

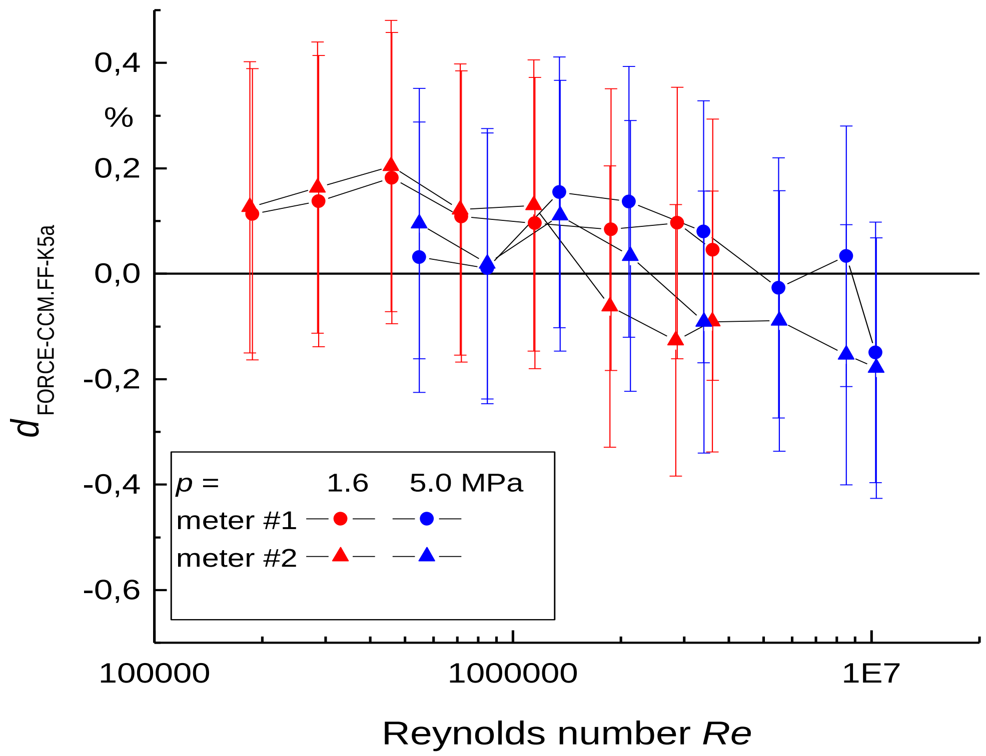


Fig. 4.4: Plot of differences FORCE-KCRV$_{CCM.FF-K5a}$ versus Reynolds number Re both meters (turbine and USM);

5 SUMMARY, FINAL REMARKS

The differences for the meter deviations as given in Fig. 4.2 and 4.3 are evaluated in comparison with their expanded uncertainty by means of the (unsigned) degree of equivalence defined as:

$$En = \frac{|d|}{U(d)}$$

The Fig. 5.1 shows the overall result for the comparison (average for both meter) utilizing the data out of Fig. 4.3 and 4.4.

<u>The final outcome of this inter comparison is the full equivalence of the measurements performed by FORCE for high pressure natural gas with the actual key comparisons reference value of CCM.FF-K5a.</u>

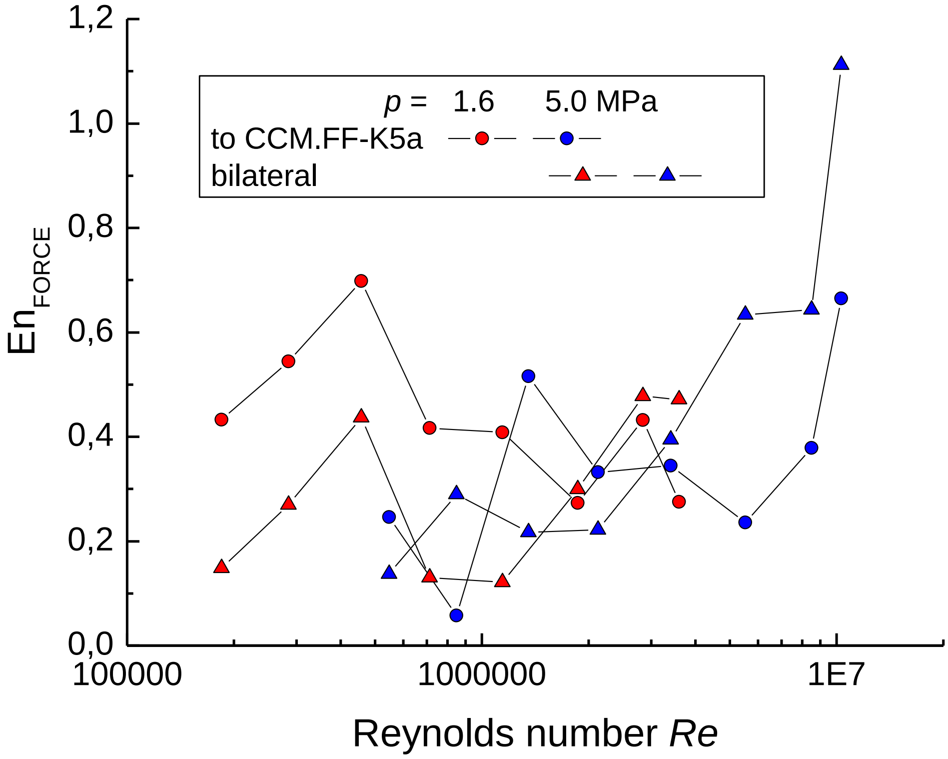


Fig. 5.1: Plot of degree of equivalence (En) versus Reynolds number Re (average of both meters);

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