Metrology for Real-World
Domestic Water Metering

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EURAMET project No. 1506
EURAMET Pilot study

Validation of standards for liquid flow rate under dynamic flows

FINAL REPORT

Pilot
CETIAT/France

Co-pilots
CMI/Czech Republic
PTB/Germany

May, 2022

Contents

1 Introduction

The aim of this pilot study is the assessment of the metrological comparability concerning dynamic flow profile capability of the dynamic test rigs in the framework of the EMPIR project 17IND13 METROWAMET - Metrology for real-world domestic water metering. The transfer standard (also called "validation module" hereafter) consisted of a Pelicase including the following main elements: Emerson MicroMotion Elite CMFS040M Coriolis Mass Flow Meter, Emerson 5700 Transmitter, Keller PR23 pressure sensor, Rosemount Pt100 Class B HART temperature sensor and was as the transfer standard. The pilot study was performed by means of three flow profiles with volumes of approximately 50 L, 80 L and 100 L simulating (representing) dynamic flow load changes in a flow rate range up to 1600 l/h.

The selected flow profiles were determined on the basis of previous studies of consumption data from various apartments and apartment buildings in some EU countries. These data were evaluated in relation to flow rates, their durations and speed of flow changes. The flow profiles were chosen with respect to the laboratories capabilities and so that the flow profiles are statistically representative of the actual water consumption in households. Each flow profile represents a different situation, for which the participating laboratory had to demonstrate its capacity to handle different flow profiles. In particular:

- Flow profile No. 1: starts with a medium flow rate and ends with a medium flow rate
- Flow profile No. 2: starts with a high flow rate and ends with a medium flow rate
- Flow profile No. 3: starts with a zero flow rate and ends with a medium flow rate.

This unprecedented inter-comparison gives a first overview of the calibration and measurement capabilities of eight European National Metrology Institutes (NMI) and Designated Institutes (DI) regarding dynamic flow measurements.

2 Participants and planning

The participants and time schedule are shown in the Table 1. Each laboratory was asked to arrange the transport to the next participating laboratory and thus paid for the cost of shipment of the package to the next laboratory. The pilot study started in September 2020 in the pilot laboratory CETIAT and finished in February 2021, just according to the planned time schedule with very small delay due to some transport issues.

Table 1 – Participants and time schedule

	Institute	Country	Contact	Date
1	CETIAT (PILOT)	France	Florestan Ogheard florestan.ogheard@cetiat.fr	September 2020 + February 2021
2	PTB	Germany	Heiko Warnecke heiko.warnecke@ptb.de	September 2020
3	FORCE	Denmark	Johan Bunde Kondrup jbko@forcetechnology.com	October 2020
4	CMI	Czech Republic	Miroslava Benková mbenkova@cmi.cz	October 2020
5	RISE	Sweden	Oliver Büker oliver.buker@ri.se	November 2020
6	DTI	Denmark	Søren Haack sorh@teknologisk.dk	November 2020
7	VTT	Finland	Huovinen Mika Mika.Huovinen@vtt.fi	December 2020
8	UME TUBITAK	Turkey	Bülent ÜNSAL bulent.unsal@tubitak.gov.tr	January 2021

3 Validation Module

The validation module consisted of a Pelicase including the following elements (figures 1, 2):

1. Emerson MicroMotion Elite CMFS040M Coriolis Mass Flow Meter
2. Emerson 5700 Transmitter with 40 ms logging of flow, pressure and temperature
3. Keller PR23 Pressure Sensor
4. Rosemount Pt100 Class B HART Temperature Sensor
5. Three-way valve to choose Upstream ("AMONT" in French on the label) or Downstream ("AVAL" in French on the label) pressure measurement. The valve should be positioned so that the measured pressure is the one which is changed by your flow change generator: upstream ('AMONT") if the flow generator is upstream of the validation module, downstream in the contrary.
6. DELL Laptop (including flow device and DAQ software) with power supply and 1 meter USB cable to connect to the validation module was also provided.

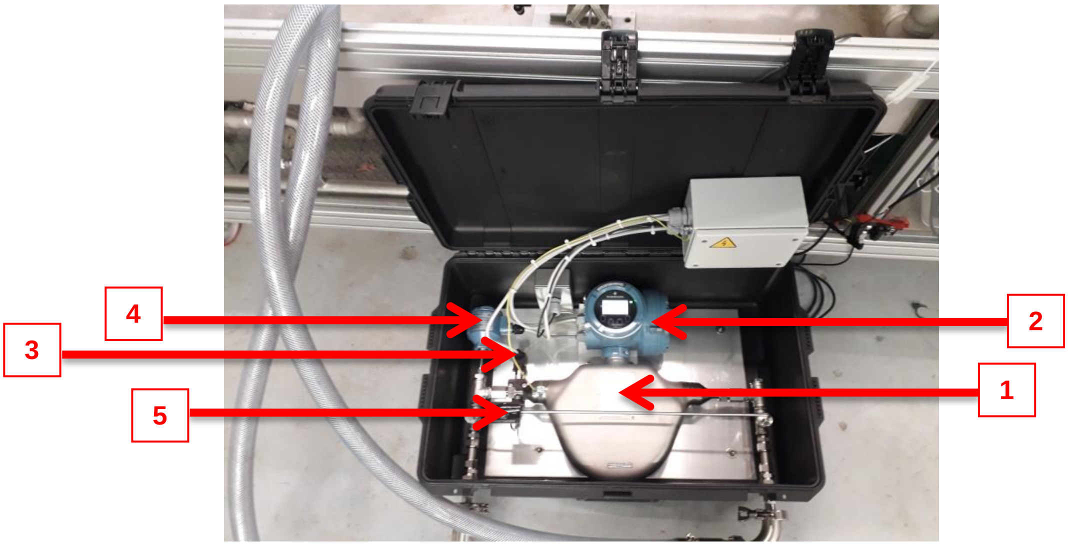


Figure 1: Inner view of the validation module

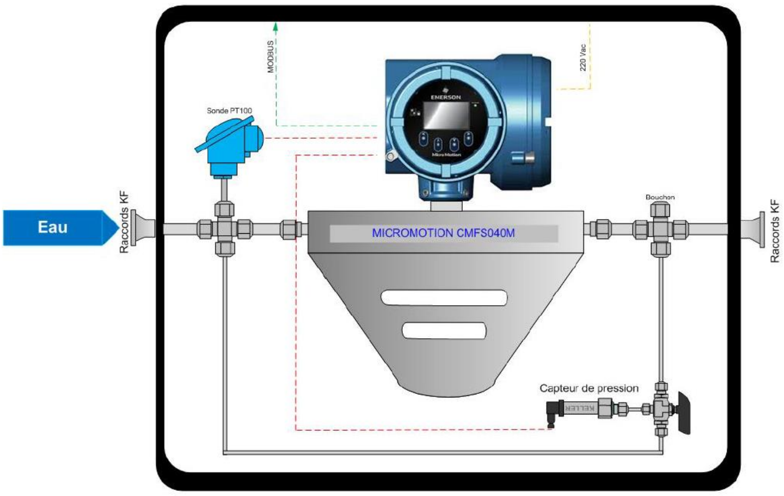


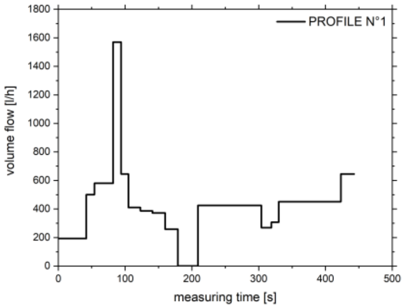
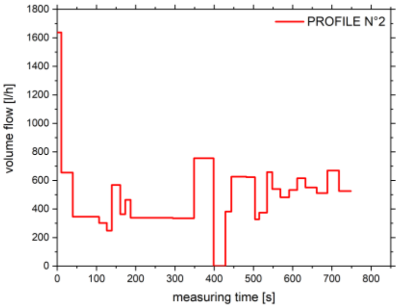
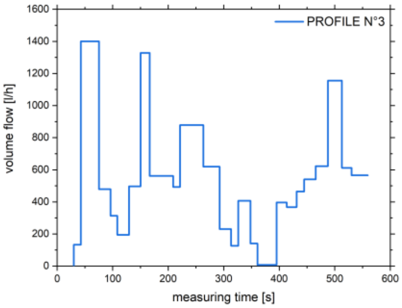
Figure 2: Schematic of the validation module

4 Measurement procedure

4.1 Dynamic flow profiles

The following flow profiles (Table 2) proposed and agreed by the METROWAMET project partners were used. Each participating laboratory could decide on the flow profiles to be measured based on the maximum measurable volume of its primary standard.

Table 2 - Dynamic flow profiles

N°1, 50 L		N°2, 100 L		N°3, 80 L	
Measuring time [s]	Volume flow [l/h]	Measuring time [s]	Volume flow [l/h]	Measuring time [s]	Volume flow [l/h]
0	193	0	1638	0	0
42	501	10.481	655.2	30	133.2
54	580	39.662	345.6	42.673	1400.4
82	1570	106.584	302.4	75.298	478.8
94	645	126.459	248.4	96.197	313.2
105	410	138.97	568.8	108.364	194.4
123	387	160.698	363.6	129.474	496.8
141	372	173.542	464.4	150.319	1328.4
160	258	187.18	338.4	166.648	561.6
179	0	294.21	334.8	208.84	493.2
209	425	348.642	756	221.344	878.4
304	269	398.457	0	263.201	619.2
319	307	428.457	381.6	292.573	230.4
330	451	443.699	626.4	313.311	126
423	645	482.067	622.8	326.245	406.8
443	645	504.031	327.6	348.129	140.4
		514.688	374.4	360.654	7.2
		534.509	658.8	395.113	396
		547.976	540	413.505	367.2
		568.824	482.4	431.225	464.4
		590.919	532.8	444.863	540
		611.527	615.6	465.711	622.8
		632.655	550.8	487.675	1155.6
		661.237	511.2	512.853	612
		688.411	669.6	530.147	565.2
		718.215	525.6	559.52	565.2
					

4.2 Test rigs

All participating laboratories were partners of the EMPIR project 17IND13 Metrowamet - Metrology for real-world domestic water metering and used their own calibration procedures to calibrate the transfer standard. In Table 3 an overview of the participating laboratories, the type of facility, calibration procedure and references for further reading is given. All laboratories used a dynamic method of measurement and are independent.

Table 3 – Participants and information about used test rigs

	Institute	Country	Test rig, method of measurement	Flow profile measured (No.)	Flow change (s)	Flow change technology
1	CETIAT (PILOT)	France	Gravimetric with weighing system See annex A and references: [3, 4, 5]	1, 2, 3	< 1	Fast valves
2	PTB	Germany	Gravimetric with weighing system See annex B and reference [6, 7]	1, 2, 3	<0.1	Critical Nozzles
3	FORCE	Denmark	Gravimetric with weighing system See annex C	2		Fast valves
4	CMI	Czech Republic	Volumetric with piston prover See annex D	1, 2, 3	<0.32	Fast piston position changes
5	RISE	Sweden	Volumetric with piston prover plus integrated measuring system (IMS) See reference: [8] and annex E	1, 2, 3	< 0.1	12-bit digital valves (pneumatically controlled modular on–off bits of binary sized flow resistors)
6	DTI	Denmark	Gravimetric with weighing system See annex F and reference [9]	1, 2, 3		Fast valves
7	VTT	Finland	Gravimetric with weighing system See annex G	1, 2, 3		Fast valves
8	UME TUBITAK	Turkey	Reference flow meter See annex H	1		Fast valves

4.3 Measurement quantity

The pilot study was based on comparing the relative error of the transfer standard as determined by the participating laboratories. The relative error ε (%) is defined as:

$$\varepsilon = \frac{q_{vm} - q_{ref}}{q_{ref}}$$

where q_{vm} is the indicated flow rate of the validation module, q_{ref} is the reference flow rate (test rig). Additionally, a detailed analysis of the realized test profiles was performed (sect. 7).

The validation module pulses output has been used by all participants, with a pulse mass set to 1 g per pulse.

4.4 Measurement conditions and protocol

The participating laboratory ensured the following conditions during the measurements:

- water temperature: 20 °C ± 5 °C;
- ambient temperature: 20 °C ± 5 °C;
- ambient humidity: from 30 % to 80 %;
- atmospheric pressure: from 86 kPa to 106 kPa.

Before starting the calibration, it was necessary to leave the validation module in the laboratory for at least 8 hours in order to acclimatise.

The participating laboratories performed the dynamic calibration in accordance with their internal calibration procedures, and the following requirements:

- Install, purge and warm-up the validation module using your internal procedures. The package must be laying horizontally as shown in Figure 1.
- Perform a "zero-point adjustment" of the validation module using the protocol provided in section 3.1 of the pilot study protocol. Note the zero value displayed after zero calibration.
- Connect the desired output (4 mA - 20 mA, pulses, or both) to your test rig's acquisition system.
- Record all calibrations measurements using MODCOM, following the procedure provided in section 3.2 of the pilot study protocol. At the same time, record all calibration measurements (from the validation meter analog/pulse output(s) and all relevant parameters (i.e. water pressure and temperature) using your test rig's DAQ system.
- Perform a measurement (recordings on both MODCOM and your data acquisition system) of at least one minute AT FLOW RATE = 0 kg/h, in order to check the zero value and stability.
- Perform a dynamic calibration with water at ambient temperature ... or 20 °C ± 5 °C temperature for the at least one of the dynamic flow profiles (depending on volume of the standard), each flow profile is repeated 5 times.
- Provide the MODCOM recordings and the following calibration data (Table 4) (minimum of required data) to the pilot laboratory for each individual measurement (number of lines = 5*N flow profiles):

Table 4 - Calibration data

Profile N°	Average Upstream Pressure (bar)	Average Water Temperature (°C)	Average DUT Flow Rate (kg/h)	Average Reference Flow Rate (kg/h)	Average Reference Totalized Volume (L)	Relative Expanded Uncertainty (*k=2*)
X	X.XX	XX.X	XXX.XXX	XXX.XXX	XX.XXX	X.XX %
…	…	….	…	…		…

- Finally, perform a measurement (recordings on both MODCOM and your data acquisition system) of at least one minute AT FLOW RATE = 0 kg/h, in order to check the zero value and stability between the beginning and ending of the test.

5 Measurements results

5.1 Stability of the validation module

The stability of the validation module has been validated at the pilot laboratory (CETIAT) by performing static calibrations (constant flow rates) at 50 kg/h, 500 kg/h, 1000 kg/h and 2000 kg/h, covering the range of the flow rates comprised in the dynamic flow profiles. The average of the relative error drift determined from the measurements at CETIAT in September 2020 (start of pilot study) and February 2021 (end of pilot study) was 0.05 %. Thus, the uncertainty associated with drift of the transfer standard, assuming a rectangular distribution of the drift, was:

$$u_{drift} = \frac{0.05}{2\sqrt{3}} = 0.01\ \%\ (k = 1).$$

Furthermore, the zero drift has been studied by measuring the mass flow rate with upstream and downstream valve closed, two times for each flow profile calibration, at several participating laboratories, including the pilot laboratory (CETIAT) at the beginning and the end of the comparison loop:

- after zeroing the transfer standard, before a given flow profile calibration
- after a given flow profile calibration.

The zero values were all comprised between +/- 0.05 kg/h, leading to an uncertainty on the zero drift of the transfer standard calculated as follows:

$$u_{zero\ drift} = \frac{0.05}{2\sqrt{3}} = 0.014\frac{kg}{h}.$$

This value has been considered as negligible compared to the average flow rate values (several hundreds of kg/h) measured for each flow profile and the associated uncertainties.

5.2 Laboratory results

The following tables 5 to 12 show the laboratory results and associated uncertainties, along with the degree of equivalence calculated as described in section 6. The total volume recorded by the validation module was evaluated against the total volume measured by the reference of the respective test rig. The measurements of the three test profiles were evaluated separately given their different characteristics and the additional information that may be gained from them.

Table 5 - CETIAT's results

PROFILE	**Av. Error**	**U(*k=2*)**	**Av. Temperature (°C)**	**Av. Pressure (barg)**
PROFILE 1	0.17 %	0.20 %	21.42	1.12
PROFILE 2	0.05 %	0.10 %	21.94	1.13
PROFILE 3	-0.06 %	0.18 %	21.95	1.21

Table 6 - PTB's results

PROFILE	**Av. Error**	**U(*k=2*)**	**Av. Temperature (°C)**	**Av. Pressure (barg)**
PROFILE 1	-0.02 %	0.10 %	21.21	4.11
PROFILE 2	-0.06 %	0.10 %	20.79	4.09
PROFILE 3	0.01 %	0.10 %	21.02	4.21

Table 7 - FORCE's results

PROFILE	**Av. Error**	**U(*k=2*)**	**Av. Temperature (°C)**	**Av. Pressure (barg)**
PROFILE 2	0.04 %	0.10 %	20.16	3.08

Table 8 - CMI's results

PROFILE	**Av. Error**	**U(*k=2*)**	**Av. Temperature (°C)**	**Av. Pressure (barg)**
PROFILE 1	0.08 %	0.16 %	21.43	0.24
PROFILE 2	0.07 %	0.22 %	23.01	0.25
PROFILE 3	-0.04 %	0.16 %	20.40	0.32

Table 9 - UME-TUBITAK's results

PROFILE	**Av. Error**	**U(*k=2*)**	**Av. Temperature (°C)**	**Av. Pressure (barg)**
PROFILE 1	0.06 %	0.33 %	19.80	5.93

Table 10 - RISE's results

PROFILE	**Av. Error**	**U(*k=2*)**	**Av. Temperature (°C)**	**Av. Pressure (barg)**
PROFILE 1	0.11 %	0.10 %	20.05	4.01
PROFILE 2	0.08 %	0.10 %	20.05	3.89
PROFILE 3	0.06 %	0.10 %	20.02	3.88

Table 11 - DTI's results

PROFILE	Av. Error	U(*k=2*)	Av. Temperature (°C)	Av. Pressure (barg)
PROFILE 1	0.10 %	0.11 %	22.44	2.92
PROFILE 2	-0.26 %	0.11 %	22.56	2.91
PROFILE 3	0.01 %	0.15 %	22.06	2.91

Table 12 - VTT's results

PROFILE	Av. Error	U(*k=2*)	Av. Temperature (°C)	Av. Pressure (barg)
PROFILE 1	0.16 %	0.40 %	9.04	3.99
PROFILE 2	0.09 %	0.28 %	8.68	3.98
PROFILE 3	0.14 %	0.28 %	8.61	4.00

NOTE: VTT's water supply was directly coming from the supply network.

6 Evaluation

6.1 Evaluation procedure

The comparison reference value (CRV) and its associated uncertainty were determined for all individual flow profiles by using the weighted average of the uncertainties of the participating laboratories [1]. All results were compared against this reference value. The chi-squared test was used for a consistency check of the laboratory results. The procedure according to [2] was used.

To judge whether the results are consistent the well-known Degree of Equivalence $E_{n_{lab\,i}}$ was used. This value is defined as:

$$E_{n_{lab\,i)}} = \frac{\varepsilon_{lab\,i} - \varepsilon_{RV}}{\sqrt{U^2(\varepsilon_{lab\,i}) - U^2(\varepsilon_{RV})}}$$

where $\varepsilon_{lab\,i}$ is the error of lab i for a certain flow profile, ε_{RV} is the CRV for the error and $U(\varepsilon_{lab\,i})$ and $U(\varepsilon_{RV})$ are the expanded uncertainties (*k*=2) of those values. The (expanded) uncertainty includes the uncertainty in reference flow rate and repeatability. The repeatability is defined as the sample standard deviation of the individual errors for a given flow profile.

To take into account the drift of the transfer standard, the uncertainty $U(\varepsilon_{lab\,i})$ has been calculated as follows:

$$U(\varepsilon_{lab\,i}) = 2 * \sqrt{\left(\frac{U_{lab\,i}}{2}\right)^2 + {u_{drift}}^2}$$

where $U_{lab\ i}$ is given in the tables 5 to 12 and u_{drift} is calculated as described in section 5.1.

The value of E_n has the following meaning:

- The results of a laboratory for a certain flow point are consistent (passed) if $E_n \leq 1$
- The results of a laboratory for a certain flow point are inconsistent (failed) if $E_n > 1.2$.
- For results between $1 < E_n \leq 1.2$ a "warning level" is defined. For this particular situation the particular laboratory is recommended to check the procedures and methodology.

The comparison reference value is the uncertainty weighted average of the error and is determined as follows:

$$\varepsilon_{RV} = \frac{\sum_{i=1}^{n} \frac{\varepsilon_{lab\ i}}{U^2(\varepsilon_{lab\ i})}}{\sum_{i=1}^{n} \frac{1}{U^2(\varepsilon_{lab\ i})}}$$

where *n* is the number of participating laboratories. The uncertainty of the CRV follows from:

$$u(\varepsilon_{RV}) = \frac{1}{\sqrt{\sum_{i=1}^{n} \frac{1}{U^2(\varepsilon_{lab\ i})}}}.$$

Finally, the chi-squared test is applied to check whether the determined errors and accompanying uncertainties can be expected based on a Gaussian distribution. If so, the CRV can be accepted. The chi-squared test is defined as follows:

$$\chi^2_{obs} = \sum_{i=1}^{n} \left(\frac{\varepsilon_{lab\ i} - \varepsilon_{RV}}{u(\varepsilon_{lab\ i})} \right)^2 .$$

Note, here $u(\varepsilon_{lab\ i})$ is the standard uncertainty (*k=1*). The set of measurement results for a certain flow point is only accepted when:

$$Pr\left(\chi^2(\nu) > \chi^2_{obs}\right) < 0.05$$

where Pr stands for probability and $\chi(\nu)$ is the expected value for a Gaussian distribution. Using the CHIINV(probability, degrees of freedom: ν = n-1) function from Excel, this can be rewritten as follows for a consistent set (coverage factor 95 %):

$$\chi^2_{obs} < CHIINV(0.05; n-1).$$

Hence, if the observed chi-squared value satisfies the above equation, the CRV is accepted. If not, the result with the largest contribution to χ^2_{obs} is discarded and the test is repeated (degrees of freedom reduced by one).

6.2 Laboratory Degree of Equivalence (DoE)

Following the procedure described in section 6.1, and based on the results presented in section 5.2, the results from profile No. 2 of DTI were discarded in the calculation of the reference value (CRV) and its associated uncertainty as well as the laboratories degree of equivalence (DoE). Table 13 shows the calculated reference value for the participating labs.

Table 13 - DoE of participating laboratories

		CETIAT		PTB		FORCE		CMI		UME TUBITAK		RISE		DTI		VTT	
		U(k=2)	En	*U(k=2)*	En	*U(k=2)*	En	*U(k=2)*	En	*U(k=2)*	En	*U(k=2)*	En	*U(k=2)*	En	*U(k=2)*	En
PROFILE	1	0.20 %	0.51	0.10 %	1.04			0.16 %	0.03	0.33 %	0.04	0.10 %	0.42	0.11 %	0.29	0.40 %	0.23
	2	0.10 %	0.19	0.10 %	0.93	0.10 %	0.06	0.22 %	0.18			0.10 %	0.50			0.28 %	0.23
	3	0.18 %	0.42	0.10 %	0.10			0.16 %	0.38			0.10 %	0.45	0.15 %	0.04	0.28 %	0.46

The following figures presents the DoEs of participating laboratories and the measurement errors of the participating laboratories for each of the flow profiles, along with the CRV (red lines) and its associated uncertainty (dashed red lines).

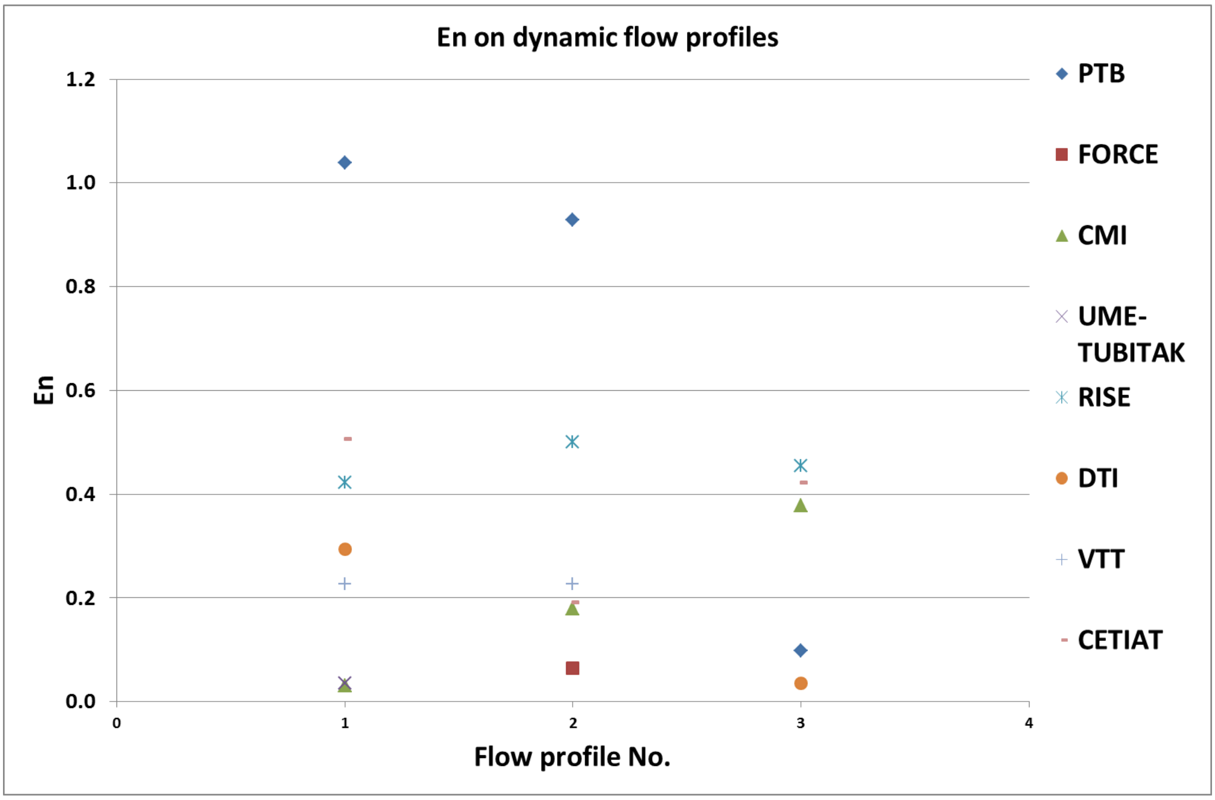


Figure 3: DoE of the participating laboratories

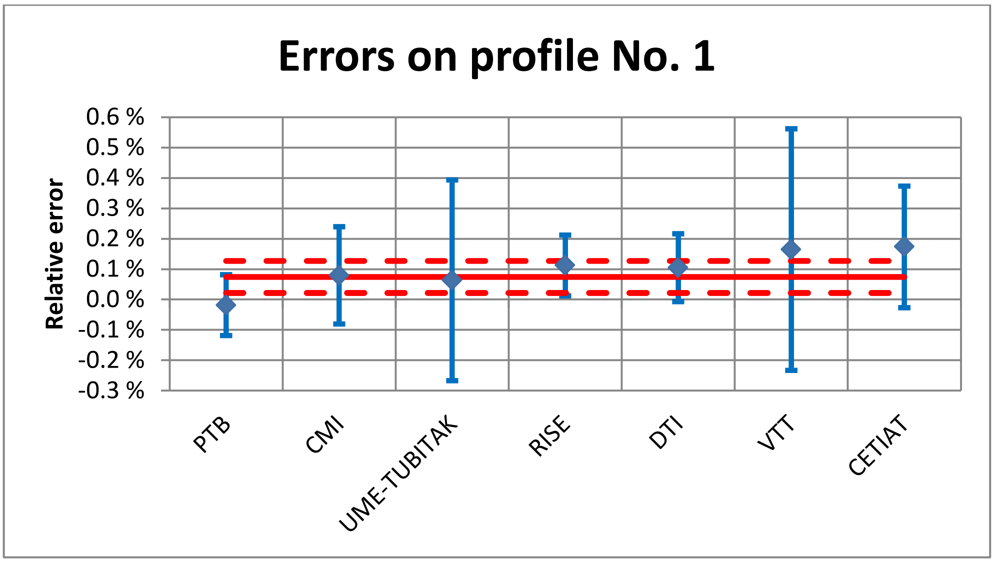


Figure 4: Measurement errors of the participating laboratories for flow profile No. 1

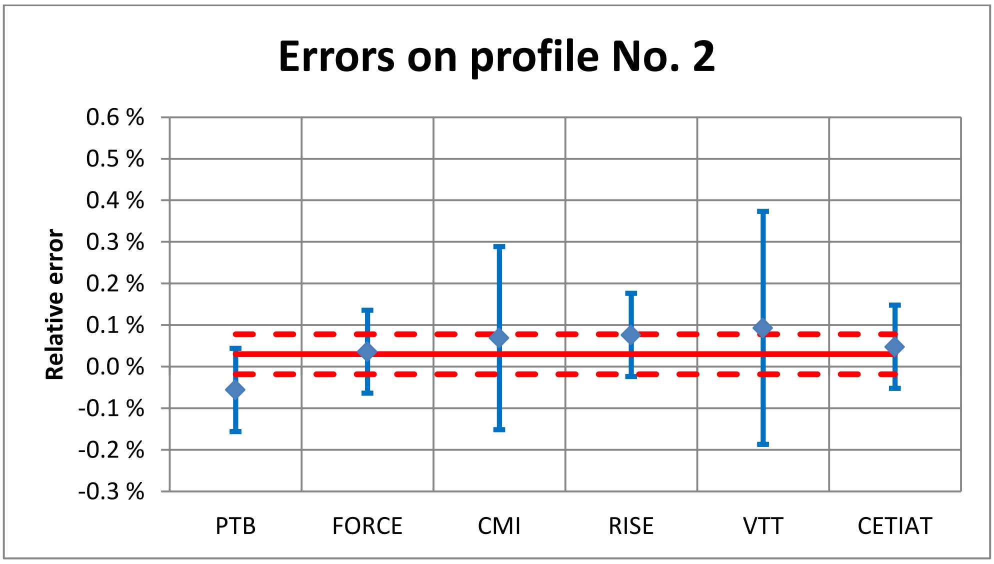


Figure 5: Measurement errors of the participating laboratories for flow profile No. 2

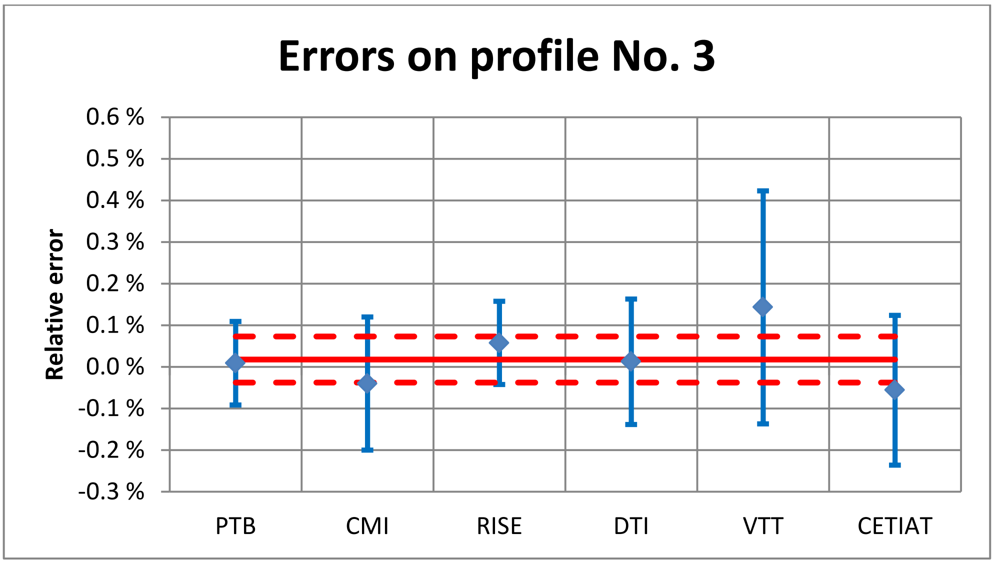


Figure 6: Measurement errors of the participating laboratories for flow profile No. 3

As shown in the figures 4 to 6 above, the relative errors for the three profiles agrees within a span of -0.1 % to 0.2 %. All technologies used for the realisation of dynamic flows perform similarly according to this. Likewise, all technologies cope similarly well on average with the different profile characteristics.

7 Analysis of the realized dynamic load profiles

With the dynamic test regime, the intercomparison goes beyond the scope of previous intercomparisons in flow measurement as the quality with which the specified profiles were realised should also be addressed [10,11]. By recording the parameters pressure, temperature and flow rate with the validation module at a frequency of 20 Hz, a good basis was created to compare more parameters between the test rigs in addition to the measurement deviation. However, these parameters are also essential for the evaluation as far as the realisation of the profiles is concerned since different technologies were used and hence the profile generation was also implemented differently.

The recording of the data was carried out with the software Modcom, which was started manually before a measurement and the data saved as a csv-file identically for all partners. In the following, the data that was also used to calculate the E_n value was further analysed.

7.1 Mass flow data

The mass data is not synchronised due to the manually started recording of the profiles. In a first step, the time of the first flow change was thus synchronised for profiles 1 and 2, and the time of the second flow change for profile 3. Furthermore, the institutes CMI and RISE used piston provers with a lower capacity volume than the profile volume. The profiles were therefore split into several parts and the sub-profiles were measured individually. The times between the profile parts were cut out to consider the mass data, so that all profiles can be compared on a common time scale, starting with zero at the beginning of each repetition and profile.

Subsequently, the recorded time-dependent mass flow data was compared to the variations of the nominal flow profiles (first column in the graphs in Appendix H). The comparison gives a first impression of the quality with which the profiles were realized on the different test rigs and provide interesting information about the characteristics of the different technologies used in profile generation.

In the case of the implementation with valves, intermittent overshooting by the control system occurs at individual flow points on the DTI and VTT test rig, so that fluctuations in the flow rate are visible. Something similar is found for the other test rigs using valves (CETIAT, FORCE and TUBITAK) as well as for PTB's test rig in which cavitation nozzles are used. There are regularly uniformly increased and decreased flow rates compared to the nominal profile. When looking at the time scale, it is noticeable for the CMI test rig where a piston prover is deployed, that there is a time stretching of the profile compared to the specification. These characteristics occur independently of the profile under consideration and all repetitions. Basically, the diagrams illustrate that all test rigs of the pilot study are capable to generate dynamic load changes reproducibly according to specification.

For further evaluations, the repetitions of a profile were combined to an average profile by the arithmetic mean of the mass flow rate. Based on these mean profiles, the residuals were calculated as the difference between the averaged profile and the nominal flow rate. The second row in appendix H shows the residuals as a line plot over the measurement time. The third row shows the residuals as a function of the flow rate in the form of a dot plot. In addition to the constant deviations in the flow at stable flow rates these plots show differences in the flow changes. When changing between flow rates, positive flow rate differences tend to occur for the DTI and FORCE test rigs and thus one-sided overshoots. For the PTB test rig, positive flow tendencies also occur after changing the flow points, resulting from the inception of cavitation. In all realisations both, negative and positive overshooting is visible, since the flow values nominally correspond to a step profile and thus to an instantaneous flow change, which is not given by the inertia of the liquid in the test rigs system.

A further aspect of the analysis of the residuals included the histogram of the residuals. For this purpose, histograms with a class division of 10 kg/h were plotted over the class mean value (cf. also last row in appendix H). The ordinate is logarithmically divided and indicates how often a flow rate difference of a certain class occurs during the profile. On the average all profiles agree well with the nominal profiles so that a main peak of the residuals is around zero. The narrower and higher this peak is, the closer the averaged profile is to the nominal profile. By this the overall quality of the profile generation for each partner can be compared. The height of the main peak varies between 1200 flow rate counts and 7500 flow rate counts for the residuals in one class, the width of the main peak varies by an order of magnitude, with the minimum being in the range of the class size of 10 kg/h.

7.2 Flow change characteristics

Looking at the flow rate changes within a profile of a participating laboratory in Appendix H, they appear to be very similar. For this reason only one of these transitions for a decreasing flow rate change and one of an increasing flow rate change respectively was investigated in more detail to characterise this part of the test rig properties.

As an example and maximum estimate the first change to a lower flow rate in profile 2 is shown enlarged in Figure 7 for seven of the participating partners and a comparable change taken from profile 1 was included in the graph for the test rig of TUBITAK. The time of the change is the synchronisation time stamp of the profiles and is shown as a dashed line in Figure 7. In addition to the example of a decreasing flow rate, the behaviour when changing from zero flow to a higher flow was considered and shown in Figure 8. Beyond the qualitative analysis, the first derivative was determined with a moving average over 10 values and, corresponding to the zero points of the second derivative, the time between the inflection points of the initial function at the flow rate change was determined and reduced by the time of averaging of half a second. These results are summarised in Table 14.

Table 14: Flow change duration based on the sign changes of the first derivative of the mass flow signal averaged over half a second. Decreasing flow change duration is a maximum estimate. Increasing flow is measured from zero flow to 381.6 L/h nominal flow rate and 425L/h for TUBITAK respectively.

Institut	Flow change duration	
	decreasing	increasing
	/s	/s
CETIAT	4.53	0.79
CMI	0.36	0.27
DTI	0.60	0.17
FORCE	0.65	0.22
PTB	0.36	0.17
RISE	2.91	0.84
TUBITAK	0.27	0.36
VTT	3.91	0.17

From Figures 7 and 8 it can be seen that the change between two flow rates takes different amounts of time for the test rigs. While the change on the test rigs of CETIAT, RISE and VTT takes more than one second until the Coriolis flow meter signal is on the next flow level, it takes less than one second on the test rigs of the other partners. The difference is caused by damping to different degrees, so the test rigs with a long change duration have no overshooting at the end of the change due to the stronger damping. In contrast, the fast changeover with little damping realized in the TUBITAK test rig, for example, leads to an oscillation of the flow rate signal. Another reason for the differences in the mass flow signal is the varying distance between flow generation and the transfer standard for the different test rigs.

Other visible effects in Figure 7 are a positive overshooting of the mass flow observed for the DTI and CETIAT test rigs at the beginning of the change process. With the increasing flow rate change, overshooting occurs in all test rigs, as can be seen in figure 8. The stability of the generated flow rates also varies for the different test rigs. The analysis of decreasing flow rate shows an analogue behaviour during the flow change as the increasing of the flow rate change. Comparing the absolute values of the durations in Table 14, the times are lower for the decreasing than for the increasing, which is due to the fact that the decreasing is a maximum estimate and the analysis of the increasing flow rate change is a medium range of about 400 L/h. The VTT flow rate change is faster after zero flow, especially in comparison to the decreasing flow change.

In general, the duration for flow changes is in the range between 0.17 s and 5 s and thus in the range that also occurs in consumption. Depending on the test rig, the duration of the change varies, whereby the time is essentially determined by the pressure specified in the system, which was not examined in more detail here. For the change after zero flow, all test rigs are in the range of 0.17 s to 0.84 s with the calculation method used.

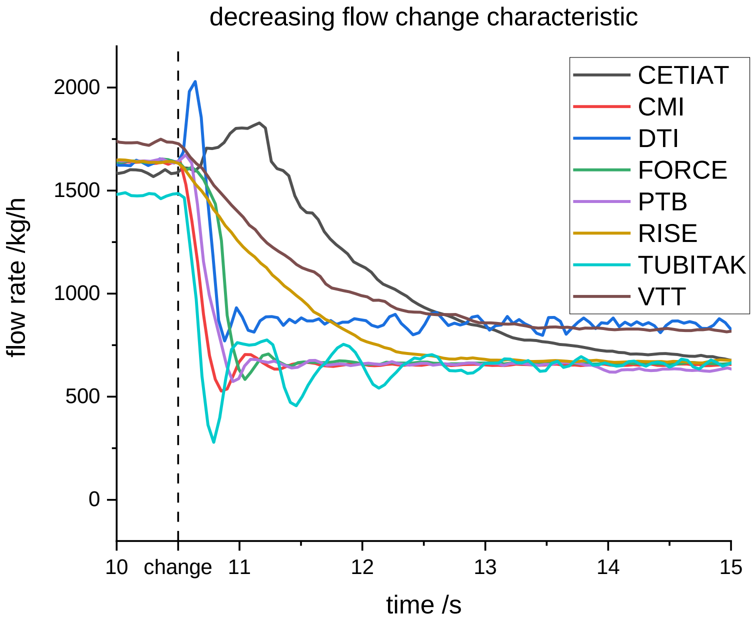


Figure 7: Maximum estimate: flow change duration realised with the test rigs of the participating laboratories: first decreasing change from profile 2 and inclusion of a comparable decreasing change of profile 1 for the TUBITAK test rig; based on the sign changes of the first derivative of the mass flow signal averaged over half a second.

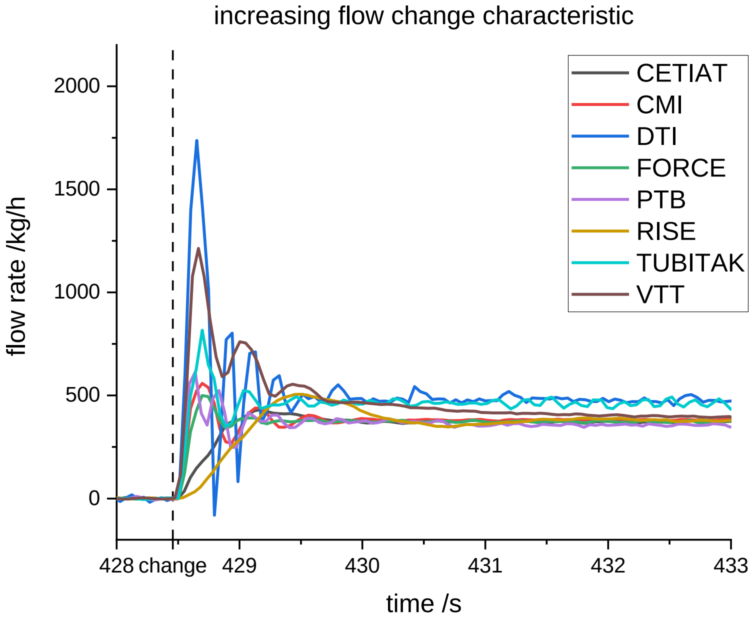


Figure 8: Flow change duration realised with the test rigs of the participating laboratories: increasing flow change from profile 2 after zero flow and inclusion of the comparable increasing change of profile 1 for the TUBITAK test rig signal; increasing flow change

duration based on the sign changes of the first derivative of the mass flow signal averaged over half a second.

7.3 Key figures comparison

To clearly compare the results, including the findings of the two previous sections for all participating laboratories, a number of parameters were determined as key figures:

The standard deviation resulting from the profile repetitions for each profile was calculated as the first parameter and then the mean value of the standard deviation was derived for a profile as a measure of repeatability.

The mean value was also be determined from the residuals as the deviation of the measured and nominal profile and thus it can be seen how well a profile corresponds to the specification on average. Positive values mean that the actual flow rate was on average higher than the nominal one and negative values mean that the flow rate was lower on average.

Furthermore, the duration until the flow rate has changed over to the next stable flow level was determined. This value is a maximum estimate for the decreasing flow change because it is the largest change of the flow rate during the dynamic load profile and was determined based on the data in section 7.2. The estimation is exemplary and was only carried out two different flow changes of profile 2 and the comparable change of the TUBITAK test rig based on one profile run. Since this analysis is about estimating an order of magnitude of this value in comparison of the different test rigs, the consideration of two flow changes, one decreasing and one increasing, is sufficient.

The fifth key figure concerns the deviation of the measured total mass from a profile, from the theoretical total mass of the profile. For this purpose, the mass determined by the corresponding reference was used and the volume of the nominal profile was converted with the density of water at 20 °C of 998.3825 kg/m³ and at 9 °C of 999.9736 kg/m³ for the data of the VTT test rig.

The results for the five key figures are summarized in Table 15 individually for the three test profiles.

Table 15 - for the different profiles and participating laboratories: summarized standard deviations of the averaged flow rates; mean of residuals; relative deviation of the measured total mass compared to the nomial total mass.

Institut	profile no.	repeatability	mean of residuals	deviation total mass
		kg/h	kg/h	%
CETIAT	**1**	6.70	10.82	2.81
CETIAT	**2**	4.65	-54.56	-10.79
CETIAT	**3**	4.60	3.81	1.05
CMI	**1**	4.73	-10.71	4.75
CMI	**2**	8.04	-5.07	4.93
CMI	**3**	11.52	4.89	5.63
DTI	**1**	63.63	152.32	37.96
DTI	**2**	41.99	131.56	28.72
DTI	**3**	47.95	146.48	27.79
FORCE	**2**	6.95	10.23	2.55
PTB	**1**	7.66	6.44	1.89
PTB	**2**	7.68	-5.22	-0.34
PTB	**3**	8.98	5.57	1.32

RISE	**1**	4.79	2.22	1.67
RISE	**2**	5.42	1.46	1.46
RISE	**3**	6.37	5.40	2.10
TUBITAK	**1**	13.34	15.77	3.43
VTT	**1**	19.38	-36.87	-8.79
VTT	**2**	4.19	-9.37	-1.94
VTT	**3**	3.21	10.49	1.83

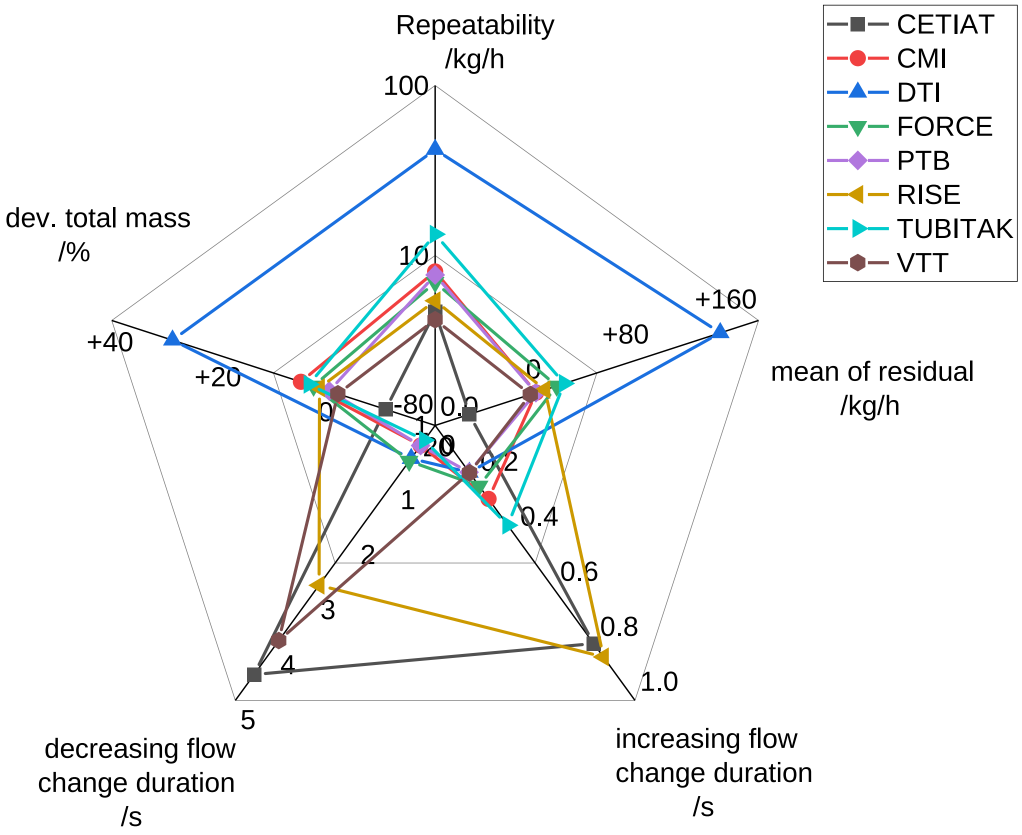


Figure 9: Repeatability, mean of residual, flow change duration for increasing and decreasing flow rates and deviation of the total mass according to table 14 and 15 for profile no. 2 of the participating laboratories and profile no. 1 for TUBITAK alternatively

These detailed investigations confirm the performance of the test rigs used in the pilot study with their different technologies. In addition, the five key factors provide a quantitative insight into the quality with which the specified profiles were realised in each case. This is particularly important when it comes to demonstrating the quality with which a given profile was realised or when it comes to demonstrably fulfilling requirements with regard to the quality of realisation.

8 Summary and conclusion

This unprecedented inter-comparison gives an overview of the calibration and measurement capabilities of 8 European National Metrology Institutes (NMIs) and Designated Institutes (DIs) for dynamic liquid flows. Three test flow profiles with different total volumes comprising rapid flow changes in a flow rate range from 7 kg/h to 1600 kg/h and steps durations down to 10 s have been used for these investigations. Moreover, the flow profiles differed distinctively in their initial and final conditions.

The degrees of equivalence (DoE) observed in this inter-comparison show that the test facilities for dynamic liquid flow calibrations of the participating laboratories are in very good agreement.

Despite the fact that three different technologies were used for the realization of the load changes, the relative errors for the three flow profiles agrees within a span of -0.1 % to 0.2 %.

The participating laboratories state expanded measurement uncertainties of their test facilities between 0.1 % and 0.4 % ($k=2$).

With a view on future broader application of this kind of calibration, an in-depth analysis of the profile realization using the individually measured data sets was carried out and key figures for the evaluation dynamic flow change realizations developed.

ANNEX A: CETIAT dynamic test rig

CETIAT's dynamic primary standards is based on a gravimetric test rig associated with two dynamic flow generators, installed downstream and upstream of the device under test as shown in figure 10.

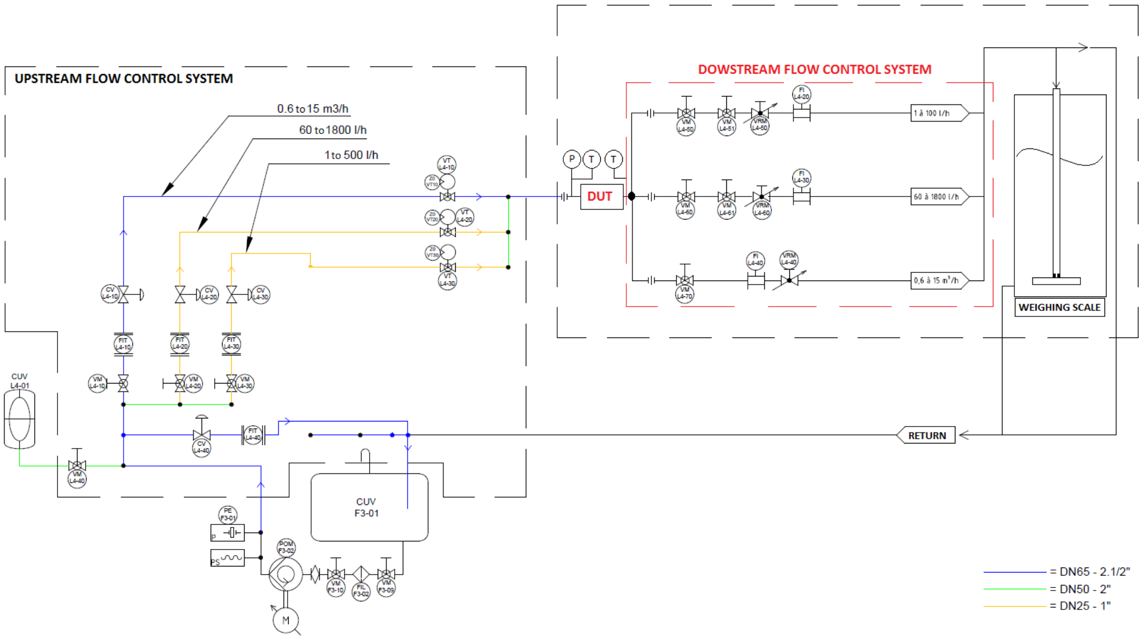


Figure 10: Schematic of CETIAT's dynamic test rig

Dynamic flow profiles are generated using a centrifuge pump associated with flow control valves and fast pneumatic valves. Depending on the need, flow changes can be generated either upstream or downstream of the device under test (DUT). Flow changes within one second can be generated within a range from 5 kg/h up to 15000 kg/h. Water temperature is controlled from 12 °C to 90 °C and measured both directly upstream and downstream of the DUT. Pressure upstream of the DUT is controlled within a range of 0.2 barg to 6 barg.

The dynamic mass flow rate is measured using a Sartorius IS150GG weighing scale (150 kg range, 1 g resolution). The flow is entering the weighing scale's reservoir using an immersed pipe equipped with a deflecting plate, which minimizes the effect of the hydrodynamic jet force towards the weighing scale's plate. The dynamic mass flow rate is calculated as the slope of the linear regression on the timestamped mass data. The mass sampling frequency is 1 kHz, which allows for the calculation of the reference mass flow rate over a minimum of 1 second of mass data, up to several hours depending on the calibration point duration. The DUT outputs (either pulses, current, voltage, or digital) are synchronized with the reference flow rate, temperature and pressure measurements using a dedicated acquisition system. The expanded relative uncertainty on the reference flow rate is 0.1 % (*k=2*) for static (constant) flow, 0.2 % (*k=2*) for dynamic (fluctuating) flow.

ANNEX B: PTB dynamic test rig

The basic experimental setup for the generation of dynamic flow profiles consists of a conventional test rig for static water flow rate measurements against a gravimetric reference (maximum: 120 kg) in which an apparatus with cavitation nozzles is integrated (Fig. 11).

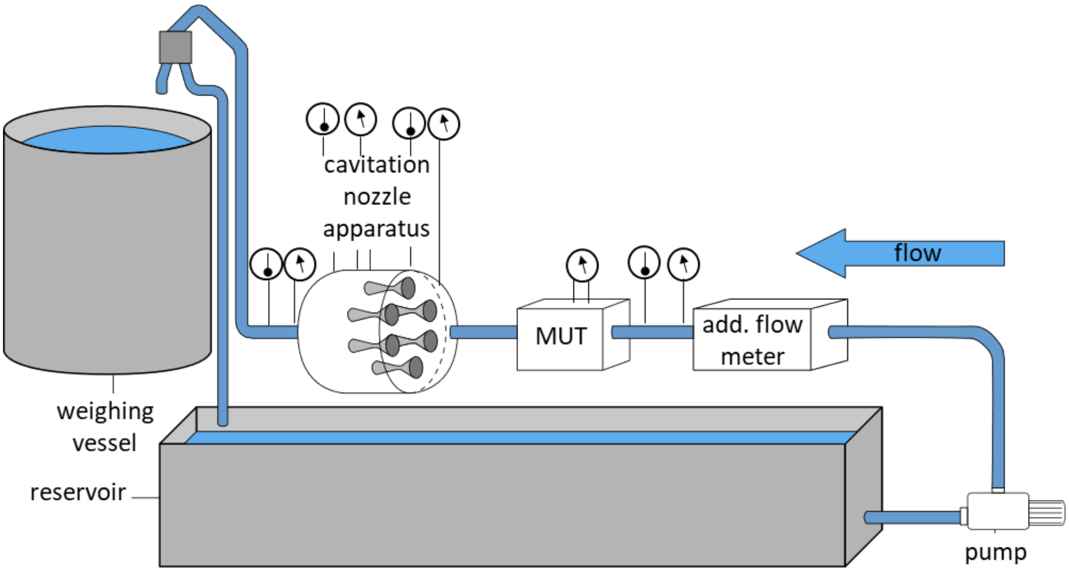


Figure 11: Principle setup of the test rig for measurements using dynamic flow rates at PTB; temperature sensors: PT100 1/10 B DIN; pressure sensors based on capacitive measuring cell with ceramic measuring membrane, accuracy: 1 %.

Static flow is generated by a pump. Rapidly changing flow rates with quickly stabilizing flows (< 0.1 s) can be generated via the connected cavitation nozzle apparatus (connection by hoses). In the apparatus six cavitation nozzles are integrated, which can be opened and closed by pneumatic stamps. The nozzles are exchangeable and using nozzles with different throat diameters variable flows can be generated. The test rig can be used for flow measurements with liquid temperatures in the range of 10 °C to 35 °C. For monitoring purposes, upstream of the measuring section, an additional flow meter, a pressure sensor and a temperature sensor are installed. Two more temperature and pressure sensors are installed downstream. A differential pressure gauge is used to measure the pressure drop across the Meter und test (MUT). The measurement uncertainty of the test rig for a conventional steady measurement regime is ± 0.1 % ($k=2$). Temperature stability is ensured by a separate cooling circuit.

Measurements are carried out as follows: In a first step, the test liquid, water, is circulated through the system at a constant flow rate to realize stable measurement conditions. A part of the flow is then diverted from this circuit via a bypass to the measuring section where the meter(s) under test (MUT) are installed. In case of mechanical meters, measurements are carried out using scanning heads, in case of electronic meters their pulse output is used directly. The conversion between volume and mass is done using the current density value, which is determined from bending oscillator measurements. The sampling rate of the system is 300 ms for dynamic measurements.

In addition to the nozzle geometry, the formation of cavitation depends essentially on the ratio of the pressure after the nozzles to the pressure before the nozzles. Therefore, the differential pressure is recorded near the nozzle holders to ensure that the pressure ratio is consistently at 0.75 or below. Furthermore, the temperature is measured in front and behind the nozzles. More in-depth information about the deployment of cavitation nozzles in liquid flow measurements can be found in [6, 7].

ANNEX C: FORCE dynamic test rig

The flow rig applied for the dynamic calibration of liquid water flow as part of METROWAMET is located at FORCE Technology, Brøndby, Denmark.

The flow rig is an extension of an existing flow rig used for calibration of flowmeters according to ISO 17025:2017. For simulation of the dynamic flow variations, an independent dynamic flow control unit (DCU) is developed to ensure a dynamic flow profile as specified in the project.

The existing rig

The operational envelope of the existing flow rig is 1 kg/h - 6000 kg/h, 0 - 10 barg and a temperature range of 5 °C - 85 °C. A schematic of the flow rig can be seen in figure 12.

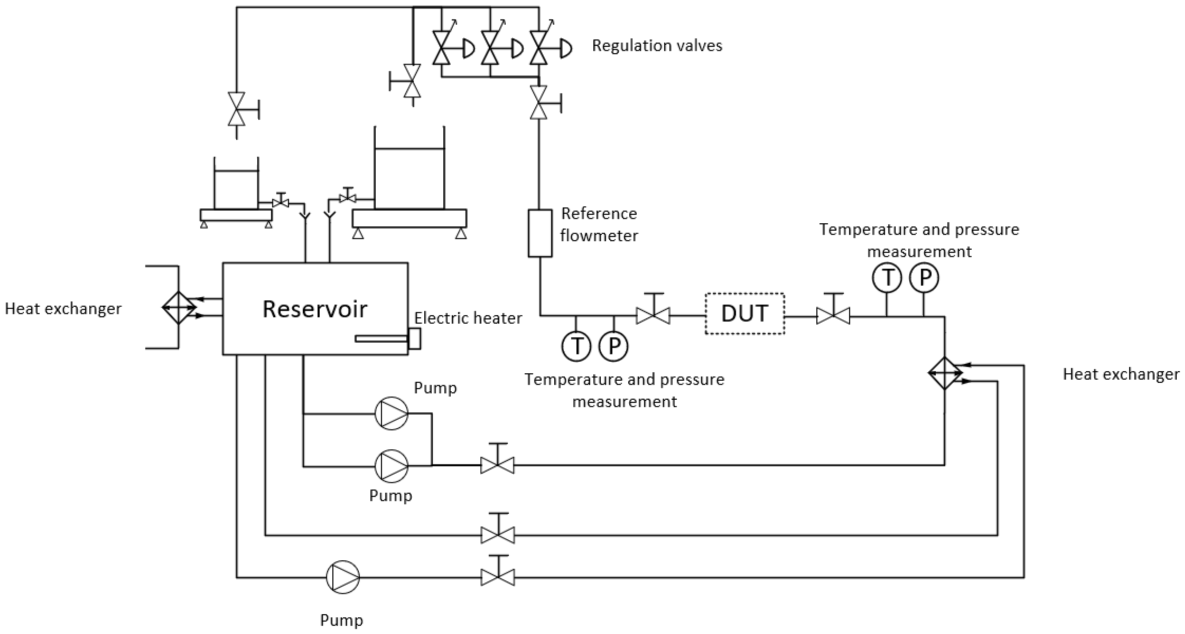


Figure 12: Schematic of existing flow rig

The flow rig is a gravimetric flow rig, where the flow is generated by a centrifugal pump (one pump to maintain a stable flow and another pump is used for a stable pressure). The flow passes through a heat exchanger which is cooled/heated with the water from the reservoir. This ensures a stable temperature at the Device Under Test (DUT) at very low flow rates. After the heat exchanger the flow passes through a temperature and pressure sensor and then into DUT. Downstream of the DUT the temperature and pressure are likewise measured and the flow rate is controlled through a reference flowmeter. The flow is led through regulation valves to adjust the flow and pressure before entering one of the two weighting scales (used depending on flow rates). These valves are not in operation when the DCU is applied for flow control. The reservoir is temperature controlled with a heating element and a heat exchanger connected to a cooling system.

Dynamic system

To perform a dynamic calibration, a stand-a-lone system is built. The stand-a-lone system can be connected to the existing flow rig, downstream the “DUT” in figure 1. The flow is designed to cover a flow range of 5 l/h - 2000 l/h and a pressure range of 0-4 barg. The system can be inserted in the place of “DUT” as seen in figure 12. The DCU can be seen in figure 13.

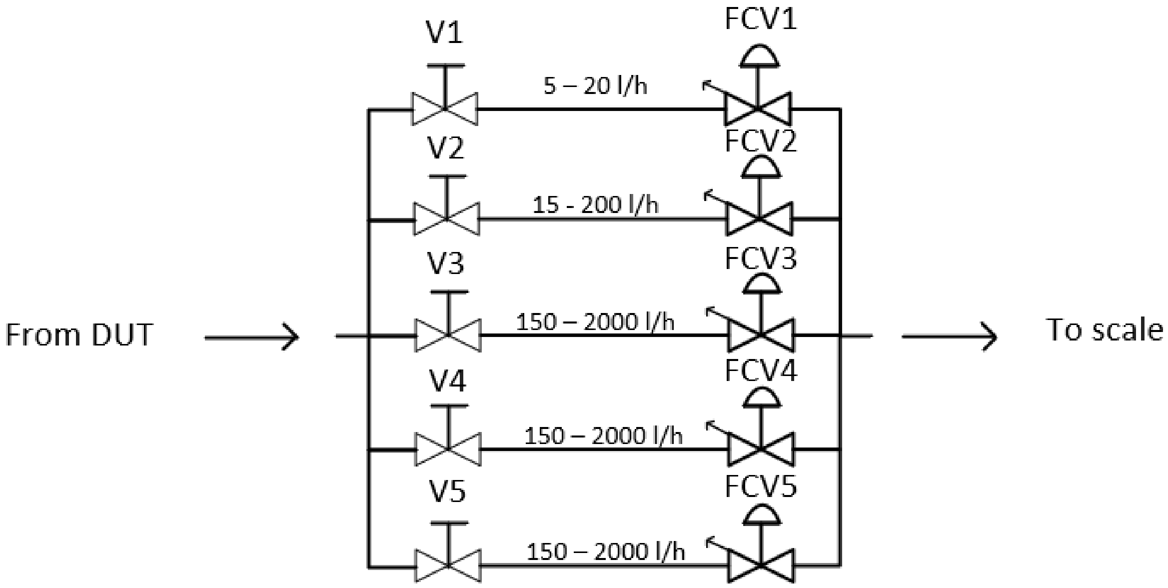


Figure 13: Dynamic control unit

The DCU consists of a number of parallel pipes, each consisting of a remotely controlled actuated flow control valve (FCV) and a rapid response on/off pneumatic valve (V) in series.

The concept of this design is to utilize the FCV for controlling the flowrates when the on/off valve is open for flow. The fast on/off valves are thus opened and closed to control the rapid changes in flow rate levels. The open signal and closing signals are given an overlay to remove flow and pressure spikes during switching to compensate for timing errors of the valves.

The sizing of the valves is chosen based on both the specified flow rates and the duration of each flow level to allow the adjustment of each of the FCV to be completed with a closed on/off valve. There is no feedback form the flow rate to the control system for the FCV’s. The positions for each valve are thus predetermined prior to the test at stationary flow rate but running through the same sequence to include any hysteresis effects of the valve positioning system.

The upstream pumps are dimensioned to a much higher flow than maximum flow rate for the DCU. The operational point for the pumps is thus located where the pressure head is (almost) constant and independent of flow rate (only depending on the pumps speed). This way the DUT is always experiences a constant inlet pressure, as is the case in most household installations.

ANNEX D: CMI dynamic test rig

The experiment was performed with a standard commonly used for calibration of flow meters (Fig. 14). This standard uses a gravimetric method using scales and the volumetric method using a piston prover. The temperature of water can be set from 10 °C to 90 °C. The standard consists of following main parts - a water source containing tanks for cold and hot water, a source of flow containing a piston prover standard or pumps (depending on method of measurement), a measuring part with measures for installation of tested meters and an evaluation device. The standard is equipped with temperature and pressure sensors for monitoring of measurement conditions.

The gravimetric method of measurement performs in the flow range (0.7 to 60) m^3/h at a pressure of (0.3 to 2) bar using a 600 kg scale as a reference. Expanded uncertainty of measurement for the gravimetric method is 0.10 %. This method was not used in this experiment.

The experiment was performed using the volumetric method where piston prover of 30 L serves as reference standard, source of flow and flow regulator. This method of measurement allows to perform static as well as dynamic measurements and performs in a flow range (0.002 to 7) m^3/h and pressure (0.3 to 6) bar. The pressure is maintained using an expansion vessel. The required tested flow is set automatically by the piston prover. When the desired initial value is reached, the measurement starts. Subsequently, the device automatically sets the required configuration of the valves for the next flow and the next flow is set.

The standard value is the amount of water delivered by the piston prover or flow evaluated from the delivered amount of water and measured time.

In the case of dynamic measurement, the program automatically monitors the required flow rate and sets this value. The time necessary for setting the flow from the previous one to the next value is smaller than 0.32 s (acceleration of the piston is 5 m^3/h per s). This process is controlled automatically.

The calculation of mass of water is based on the density of the water (evaluated from sample of water in laboratory) and actual measured water temperature.

Data were collected with period of 100 ms. The piston prover is traceable to the CMI standards via geometric method and the results are compared with the mass method at the same device. The expanded uncertainty of the standard value was determined for steady flow as 0.10 % and better. The achievable uncertainty when using dynamic measurement is 0.22 % and better.

Figure 14: View of CMI flow standard

ANNEX E: RISE dynamic test rig

The test facility used is one of the national standard water flow calibration facilities at RISE [8]. It consists of two pressurised tanks, a high pressure tank (Tank1) and a low pressure tank (Tank2), figure 15. The pressure in both tanks is generated by compressed air. The flow is generated by a pressure difference of 1 bar to 6 bar between the two tanks. The desired flow rate from less than 6 l/h to 6000 l/h is set with control valve RV1. The pressure in both tanks is controlled separately by two control valves RV4 and RV5.

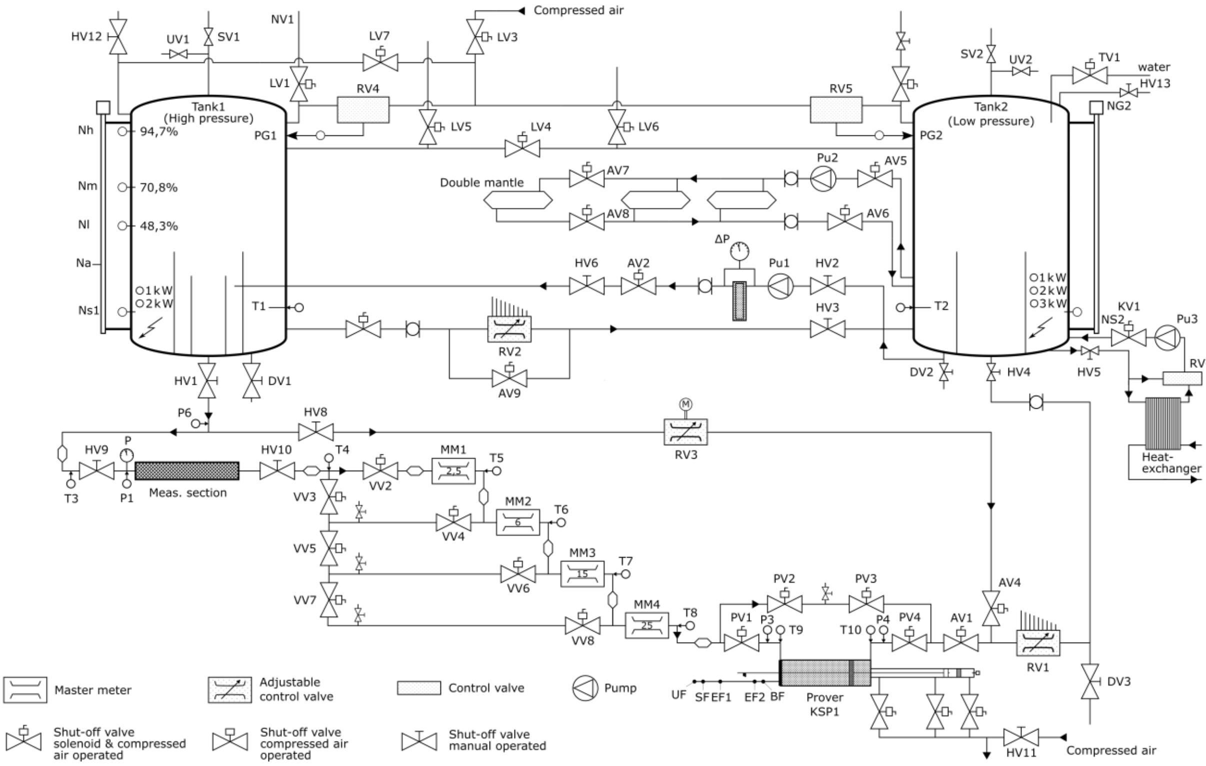


Figure 15 – Schematic drawing of RISE calibration facility VM7.

During calibration, the pressure difference method is complemented by continuous filling of Tank1 from Tank2 by means of pump Pu1. In this case, a constant high flow rate and pressure stability at constant level Na (level gauge) is maintained by setting another digital control valve RV2 in the return line (return flow into Tank2).

RV1 and RV2 are two 12-bit digital valves which provide in theory a nearly perfect linearity without any hysteresis. The digital valves operate by pneumatically controlling modular on-off bits of binary sized flow resistors (sharp-edged orifices) housed in a multi-ported body. In this case, triggering of the actuators is accomplished through pilot solenoid valves. The actuators are controlled via pilot solenoid valves. The flow through the valve can be calculated as the sum of the operating bits. Porting of the valve is manufactured very close to a pure binary progression and thus the digital valve has a linear flow rate characteristic. Dynamic flow changes are generated by RV1 and the flow in the return line is automatically adjusted by RV2 (controlled by Na). A 12” Brooks Compact Prover (BCP12) with an Integrated Measuring System (IMS) is used as reference. The BCP12 has two fixed calibrated volumes of 20 L and 60 L but can be used at any volume (up to 80 L) due to the IMS and its high-resolution linear encoder system. The expanded relative uncertainty for the measurement of static and dynamic flow rates is U(k=2) ≤ 0.10%.

ANNEX F: DTI dynamic test rig

The flow laboratory at DTI, Aarhus, Denmark contains three different test rigs covering a flow range from 6 L/h up to 1000 m^3/h. The flow rig used for in this comparison is the medium sized flow rig. The flow rig is based on a gravimetric reference system with a maximum volumetric load of 1000 kg, and calibration can be performed with water temperature from 4 °C to 85 °C. The expanded uncertainty for the static calibration using the gravimetric reference is ± 0.05 % (*k=2*).

Figure 16: Medium sized flow rig at DTI, Denmark

The newly renovated flow rig is based on a PLC-system with digitalized DAQ-system, where all data are acquired with a high temporal resolution, each 2 ms., during the entire calibration process.

For the comparison, the pulse output of the transfer standard was used as DUT output and compared to the gravimetric primary reference.

Dynamic test module

For the purpose of the METROWAMET project a Dynamic Test Module was developed and implemented into the existing PLC control system.

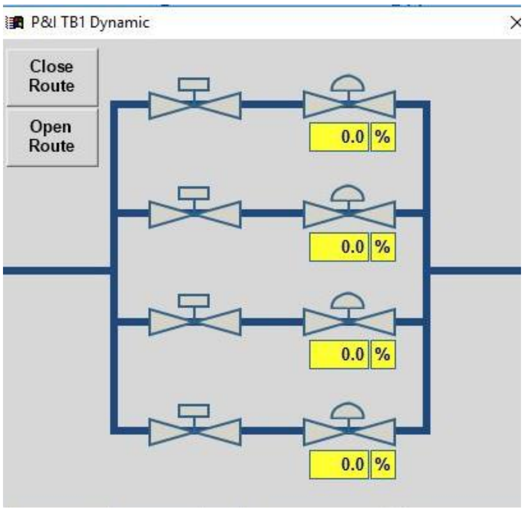


Figure 17: Dynamic Test Module added to existing system

The module is controlled by the existing system by pre-defining duration time period for the open-close valves and valve settings for the adjustable values. The module works in pairs – the two upper strings and the two lower strings. While water flows through the upper string the adjustable value is being prepare for the next flow and when the set time period for the upper string is finished the open-close valves closes while the similar valves open for the lower string allowing the next flow level.

ANNEX G: VTT dynamic test rig

VTT's test rig is based on a scale as the reference device. The test rig imitates household system: the local water supply network is used to feed the inlet and an additional pressure vessel is used to stabilize the inlet water pressure. The meter under test is installed to measurement section and after that are the valves to control the fluid flow. Four of the valves are fast on/off valves and one is adjustable valve for ramps.

The maximum mass of the scale is 800 kg and the step value of the scale is 10 g. The rig contains three temperature and pressure sensors. One temperature sensor and one pressure sensor are installed to the rig before the MUT and two temperature and pressure sensors after the MUT.

During the operation, the valves control the flow rate and it is possible to measure zero flow as well. The scale limits the measurement time. Data gathering in the rig is based on the National Instruments digital I/O-system. Temperature and pressure data is sampled with 1 kHz and the scale and MUT reading is sampled with 2 Hz.

Other parameters in the rig are the inlet pressure, which is ca. 4 bar and water temperature is ca. 4-10 degrees. The flow rate range is from 50 kg/h up to 3000 kg/h. The expanded relative uncertainty of the reference flow rate is 0.40 % (*k=2*) for dynamic flow and 0.16 % (*k=2*) for static flow over 1000 kg/h and 0.74 % (*k=2*) for static flow under 500 kg/h.

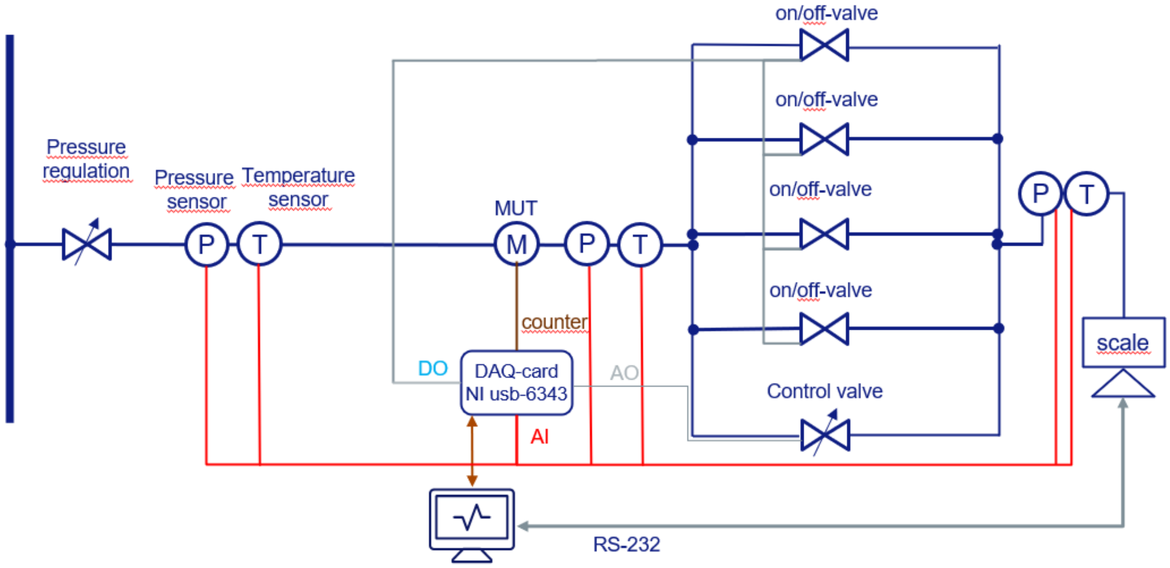


Figure 18: Schematic of VTT's dynamic test rig

ANNEX H: UME TUBITAK dynamic test rig

The dynamic flow test rig consists of Endress Hauser Promass F300 Corriolis reference flow meter and three proportional valves from the company Burkert. The valves are connected in parallel to each other and each of them can be controlled independently or together via analog signals generated through the DAQ card. The same DAQ card is also used to acquire analog and/or pulse signals from the reference flow meter and also from the meter under test. The flow is generated through a pump which circulates the flow through the water pool. The pump is able to generate maximum 8 bar of pressure which gives maximum around 1800 l/h (decreases with increasing pressure drop) flow rate.

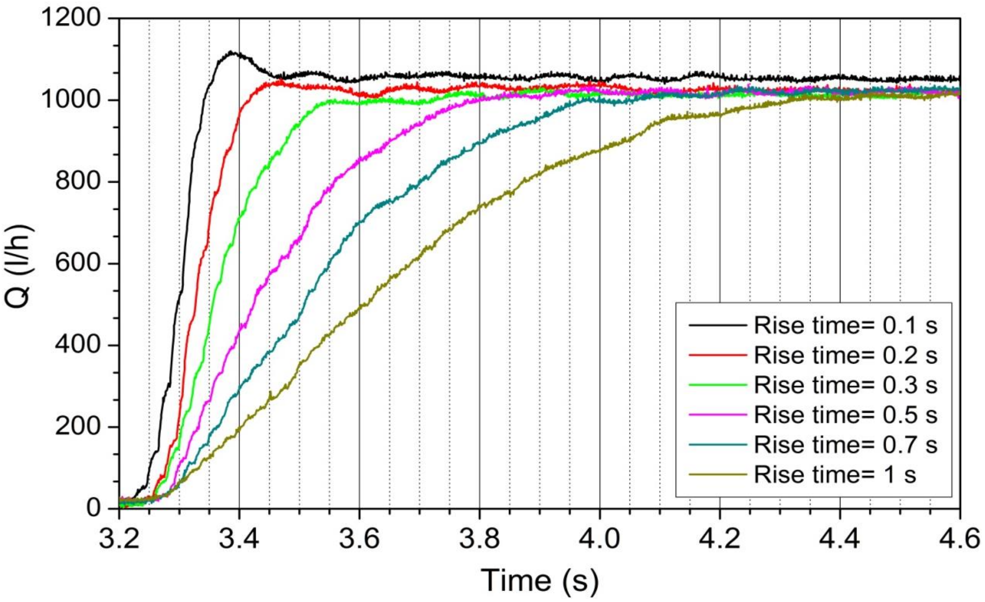


Figure 19: Instantaneous flow rate variation for various rise times

The main advantage of the system is the ability to adjust flow acceleration and deceleration.

The proportional vales allow minimum 0.1 s response time to change between two flow rate values. In the above figure, reference flow meter reaction is given for the variation of opening time (rise time) between 0.1 and 1 s. Such acceleration and deceleration control makes possible to generate various periodic and non-periodic and also any kind of instantaneous flow rate generations to test various dynamic features of flow meters.

The test rig operates at room temperature without any water temperature control.

ANNEX I: dynamic load profiles

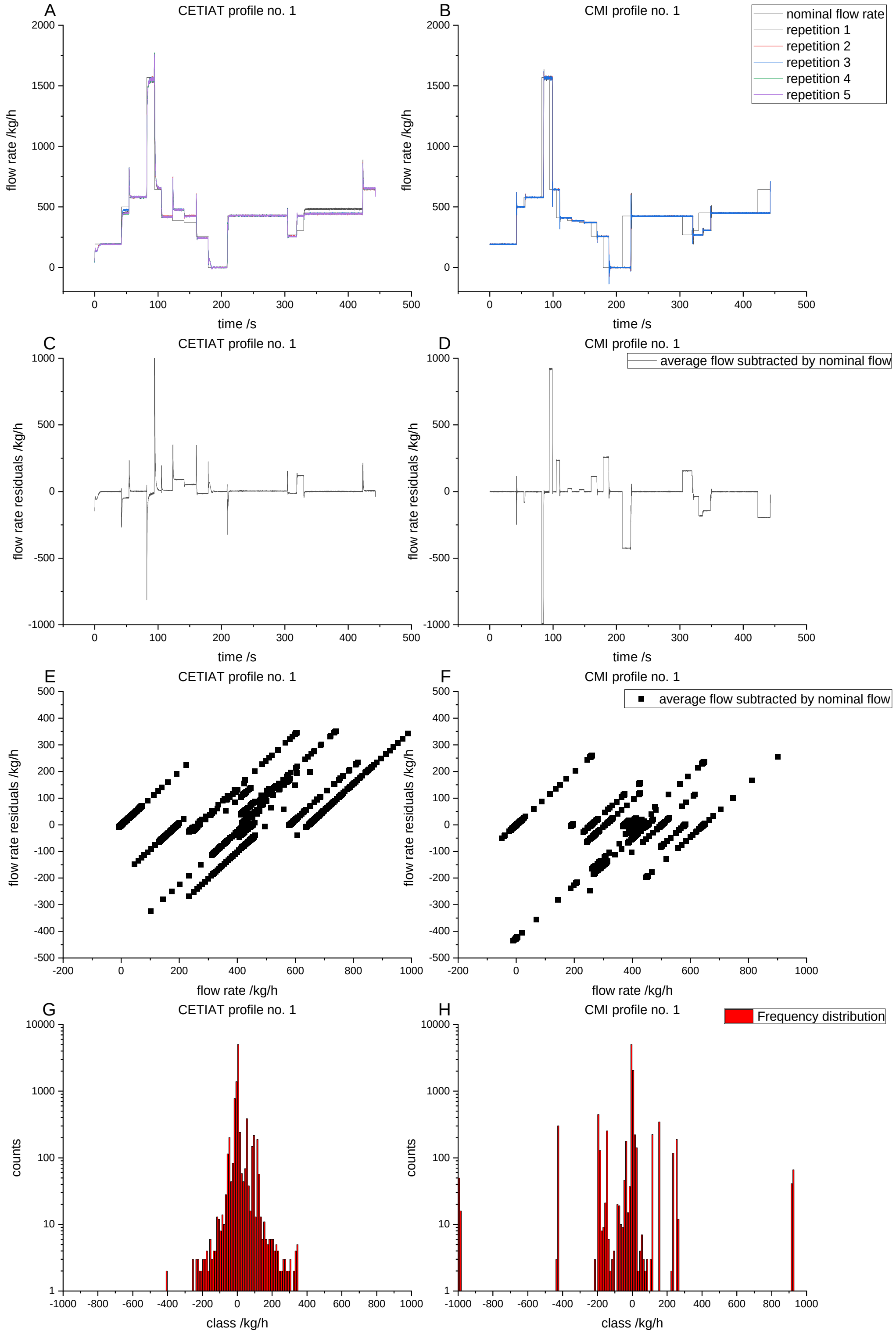


Figure 20: 1st row: continuous recorded (20 Hz) mass flow signal of the Coriolis from n profile repetitions; 2nd and 3rd row: Residuals of the averaged flow profile, plotted versus time and plotted versus flow rate (enlarged); 4th row: frequency distribution of the residuals. Each column represents measurements of one profile (no. 1) of one institute (CETIAT/CMI; Sub diagram heading).

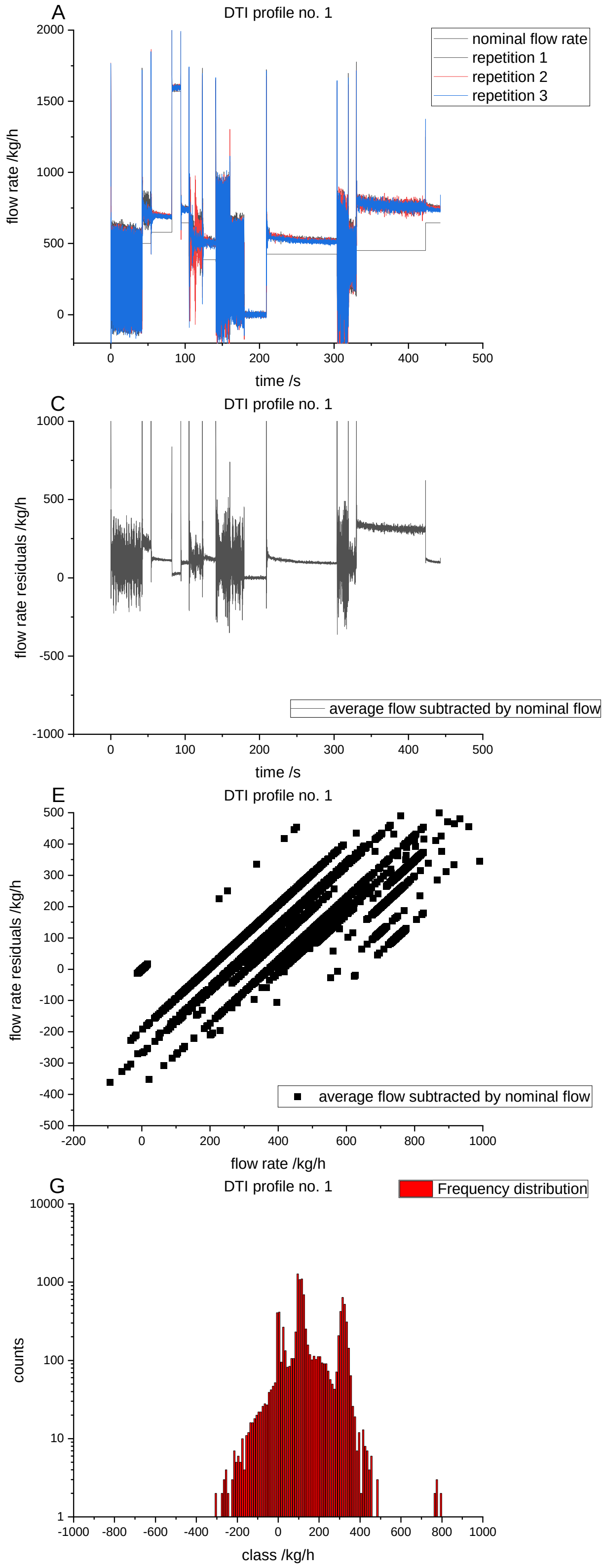


Figure 21: 1st row: continuous recorded (20 Hz) mass flow signal of the Coriolis from n profile repetitions; 2nd and 3rd row: Residuals of the averaged flow profile, plotted versus time and plotted versus flow rate (enlarged); 4th row: frequency distribution of the residuals. Each column represents measurements of one profile (no. 1) of one institute (DTI; Sub diagram heading).

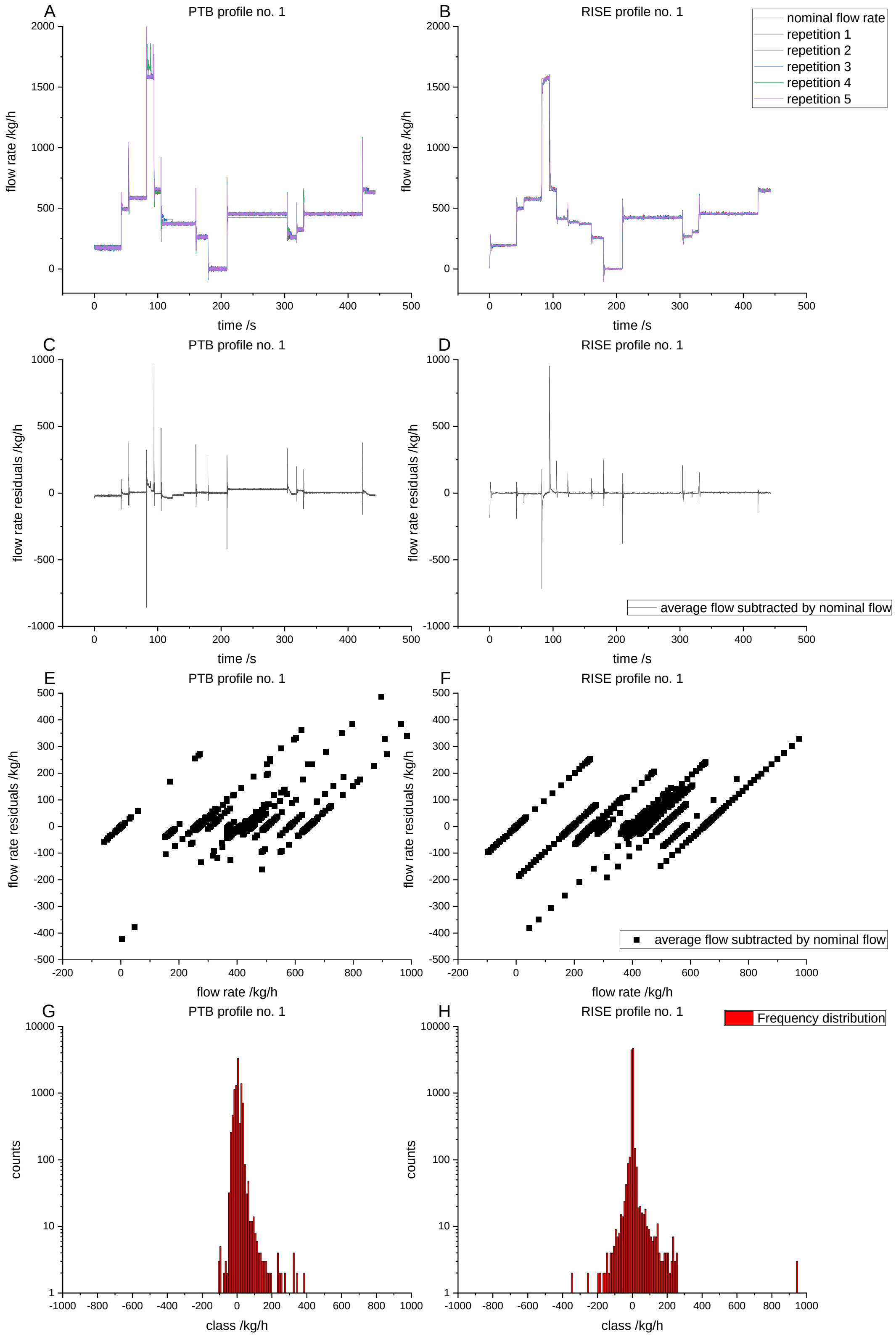


Figure 22: 1st row: continuous recorded (20 Hz) mass flow signal of the Coriolis from n profile repetitions; 2nd and 3rd row: Residuals of the averaged flow profile, plotted versus time and plotted versus flow rate (enlarged); 4th row: frequency distribution of the residuals. Each column represents measurements of one profile (no. 1) of one institute (PTB/RISE; Sub diagram heading).

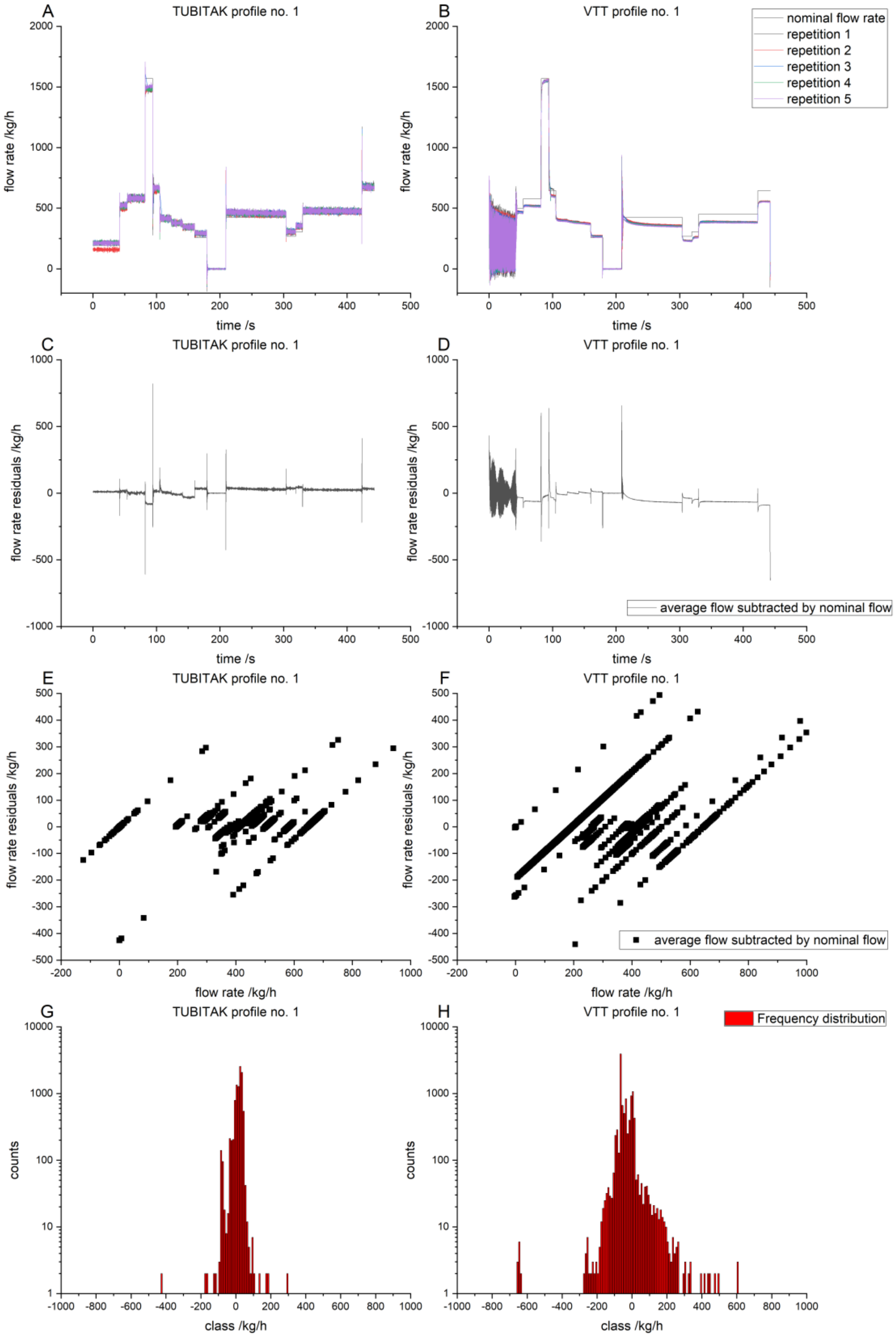


Figure 23: 1st row: continuous recorded (20 Hz) mass flow signal of the Coriolis from n profile repetitions; 2nd and 3rd row: Residuals of the averaged flow profile, plotted versus time and plotted versus flow rate (enlarged); 4th row: frequency distribution of the residuals. Each column represents measurements of one profile (no. 1) of one institute (TUBITAK/VTT; Sub diagram heading).

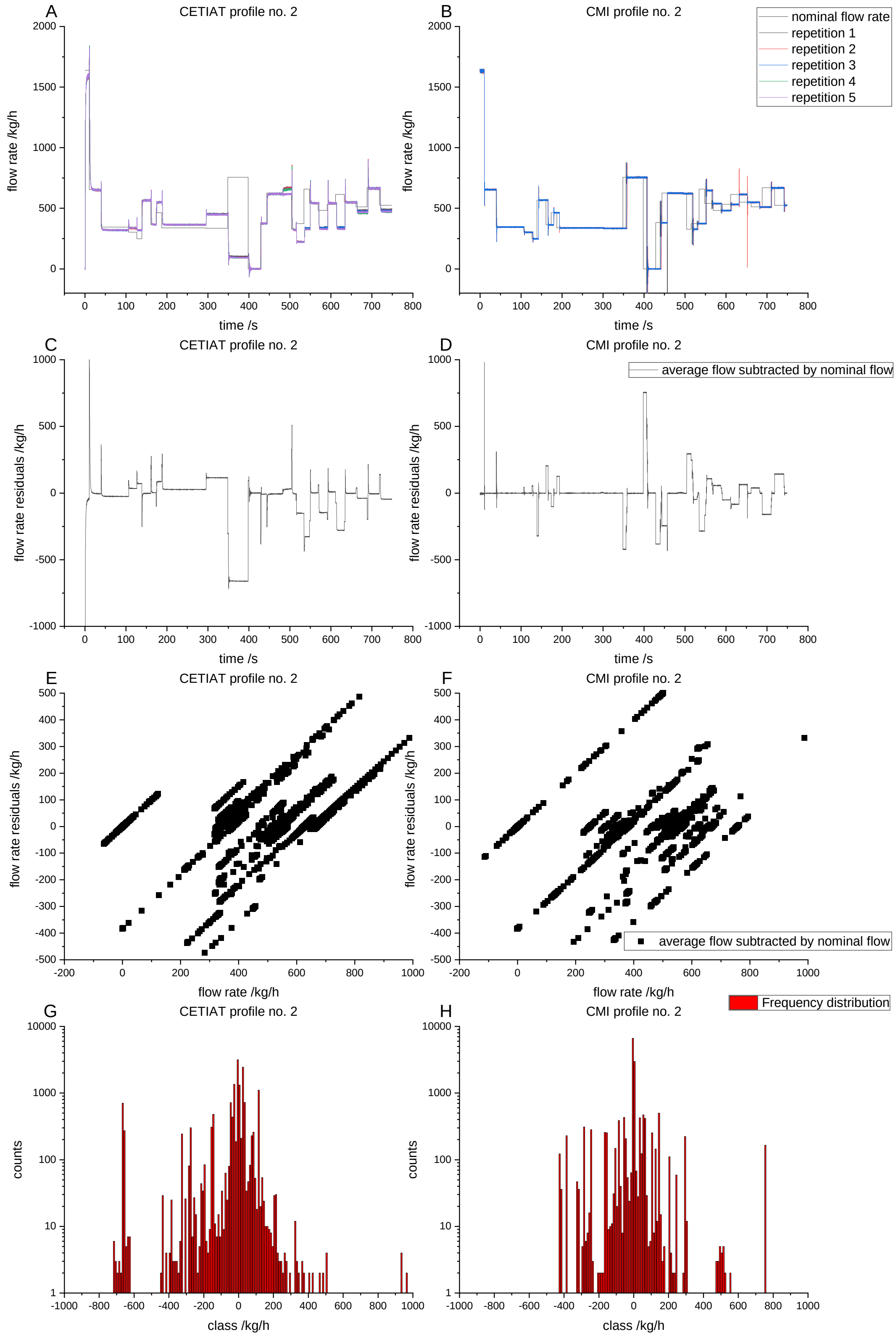


Figure 24: 1st row: continuous recorded (20 Hz) mass flow signal of the Coriolis from n profile repetitions; 2nd and 3rd row: Residuals of the averaged flow profile, plotted versus time and plotted versus flow rate (enlarged); 4th row: frequency distribution of the residuals. Each column represents measurements of one profile (no. 2) of one institute (CETIAT/CMI; Sub diagram heading).

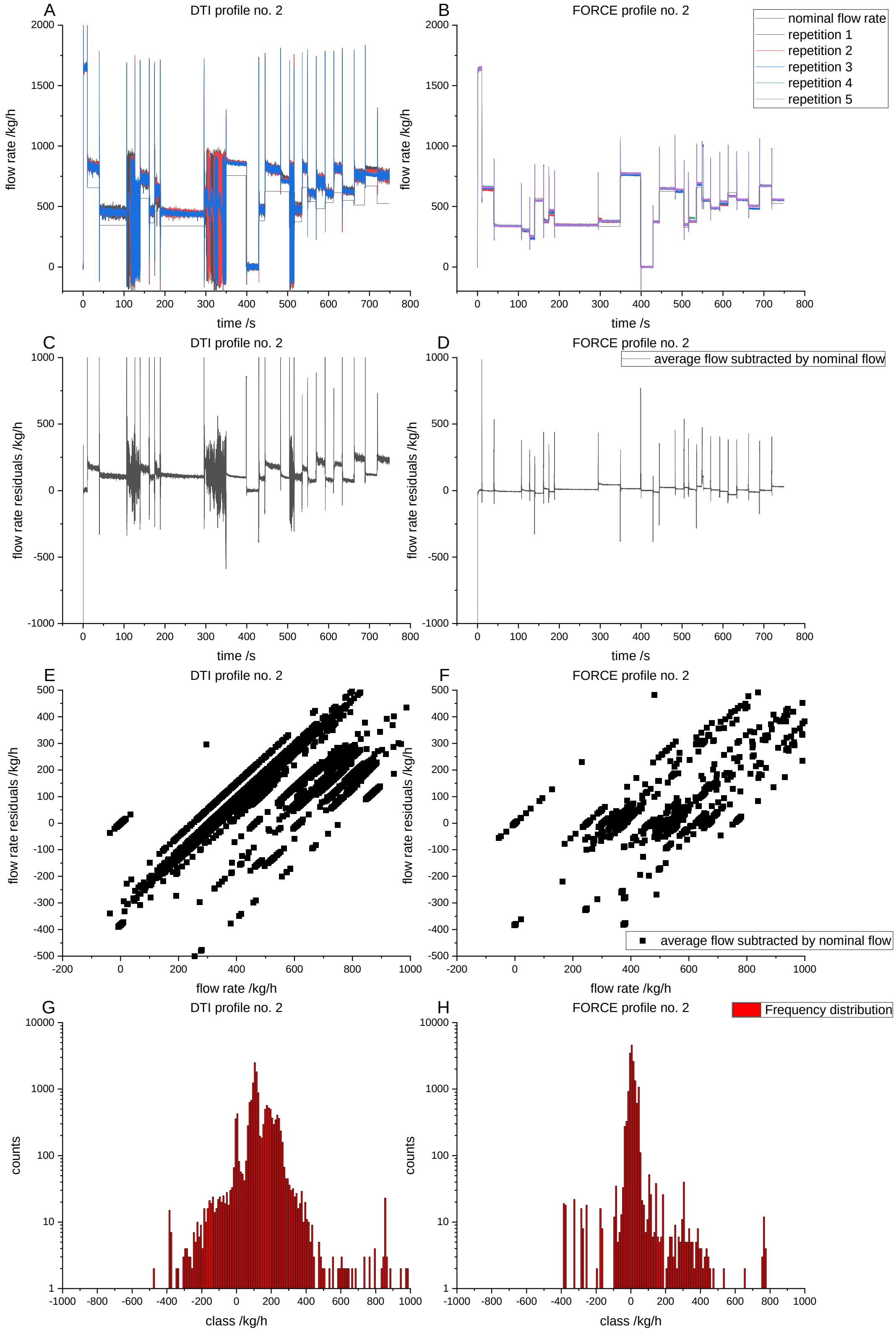


Figure 25: 1st row: continuous recorded (20 Hz) mass flow signal of the Coriolis from n profile repetitions; 2nd and 3rd row: Residuals of the averaged flow profile, plotted versus time and plotted versus flow rate (enlarged); 4th row: frequency distribution of the residuals. Each column represents measurements of one profile (no. 1) of one institute (DTI/FORCE; Sub diagram heading).

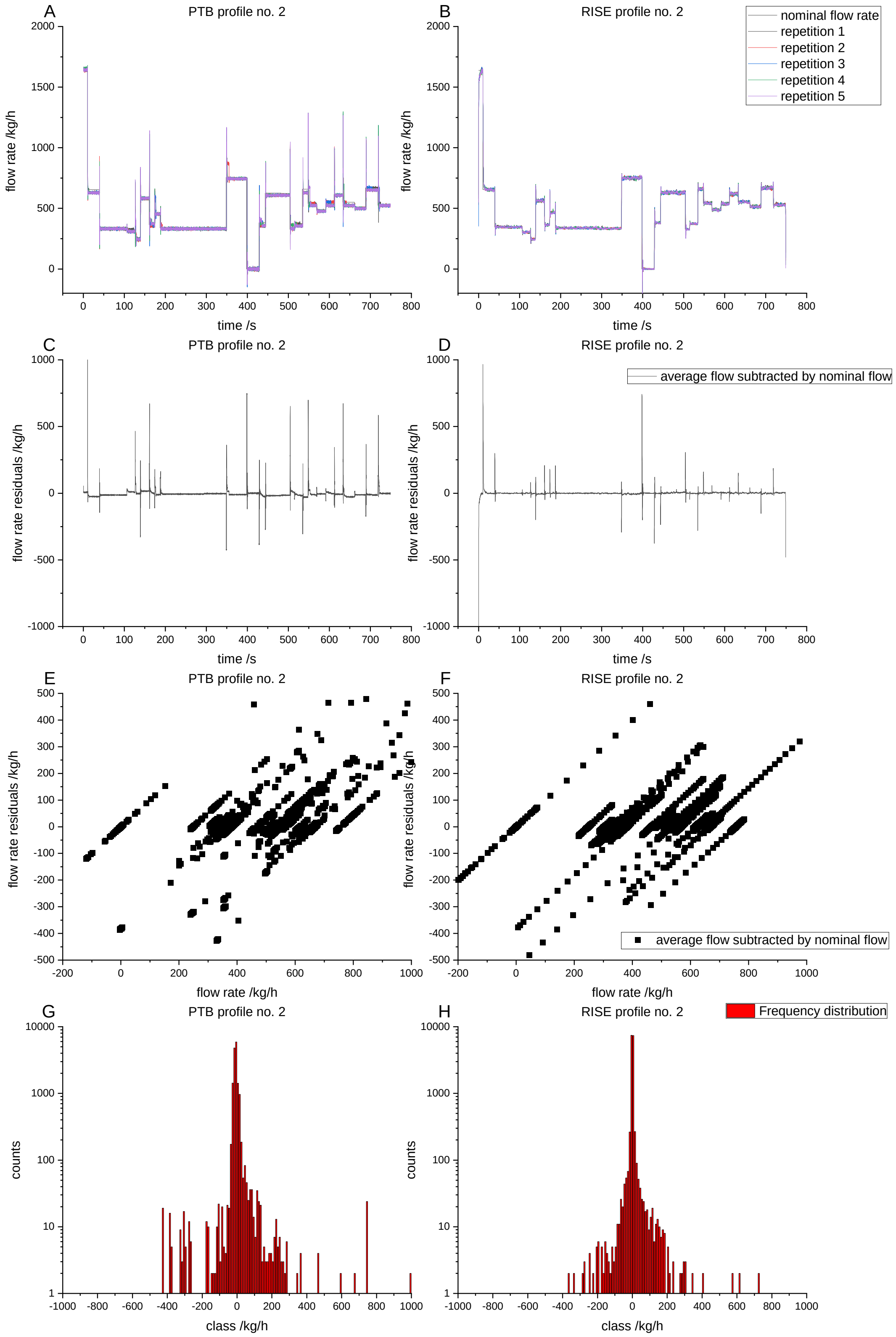


Figure 26: 1st row: continuous recorded (20 Hz) mass flow signal of the Coriolis from n profile repetitions; 2nd and 3rd row: Residuals of the averaged flow profile, plotted versus time and plotted versus flow rate (enlarged); 4th row: frequency distribution of the residuals. Each column represents measurements of one profile (no. 2) of one institute (PTB/RISE; Sub diagram heading).

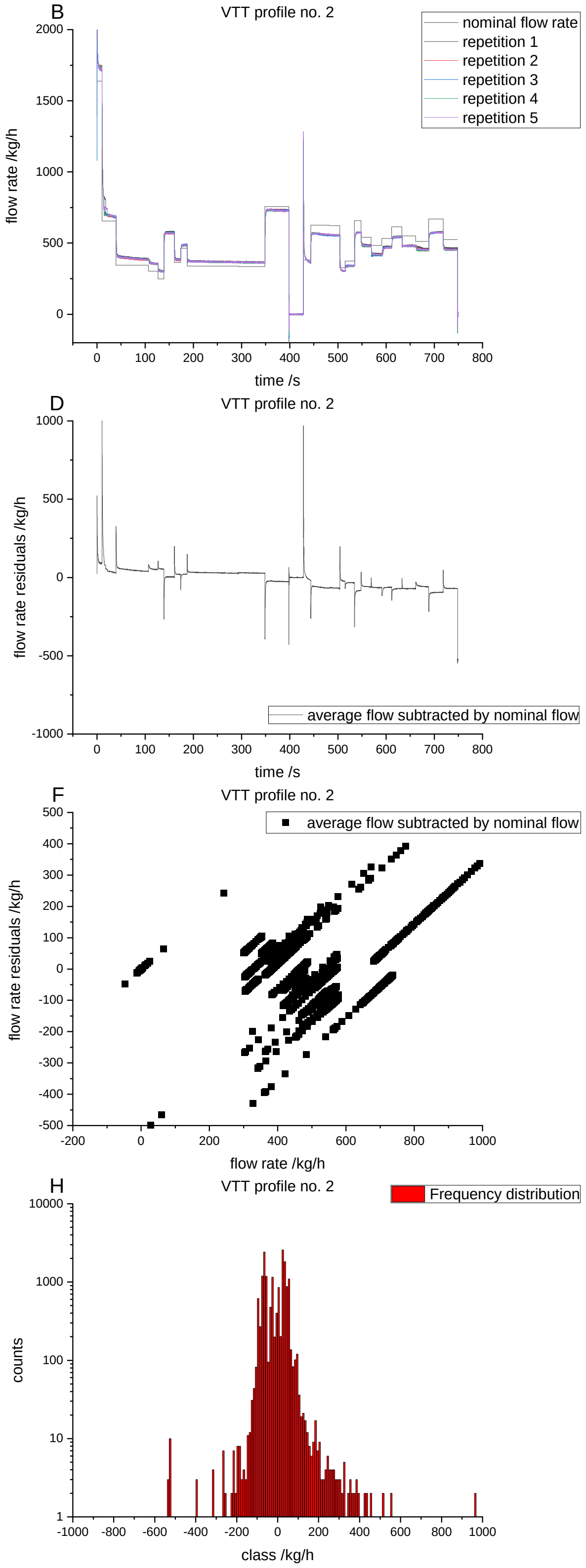


Figure 27: 1st row: continuous recorded (20 Hz) mass flow signal of the Coriolis from n profile repetitions; 2nd and 3rd row: Residuals of the averaged flow profile, plotted versus time and plotted versus flow rate (enlarged); 4th row: frequency distribution of the residuals. Each column represents measurements of one profile (no. 2) of one institute (VTT; Sub diagram heading).

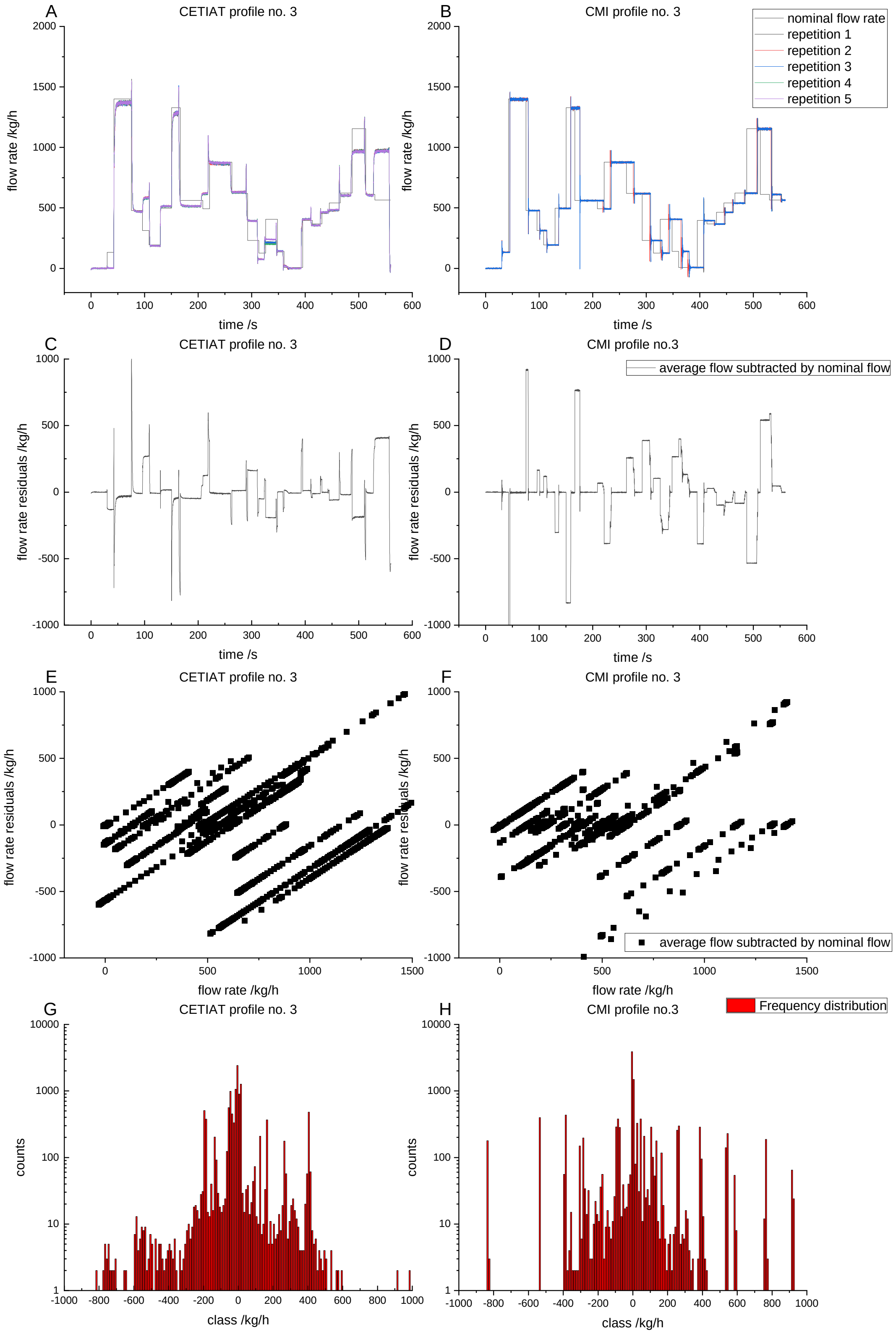


Figure 28: 1st row: continuous recorded (20 Hz) mass flow signal of the Coriolis from n profile repetitions; 2nd and 3rd row: Residuals of the averaged flow profile, plotted versus time and plotted versus flow rate (enlarged); 4th row: frequency distribution of the residuals. Each column represents measurements of one profile (no. 3) of one institute (CETIAT/CMI; Sub diagram heading).

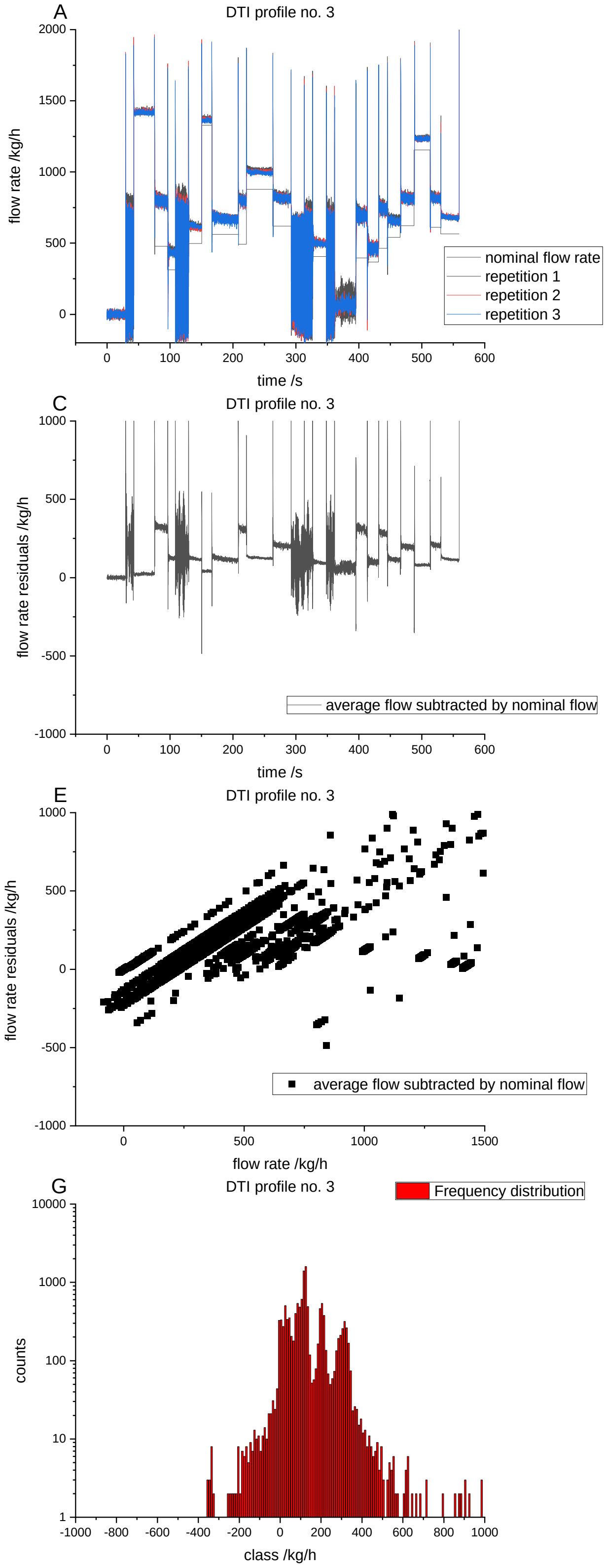


Figure 29: 1st row: continuous recorded (20 Hz) mass flow signal of the Coriolis from n profile repetitions; 2nd and 3rd row: Residuals of the averaged flow profile, plotted versus time and plotted versus flow rate (enlarged); 4th row: frequency distribution of the residuals. Each column represents measurements of one profile (no. 3) of one institute (DTI; Sub diagram heading).

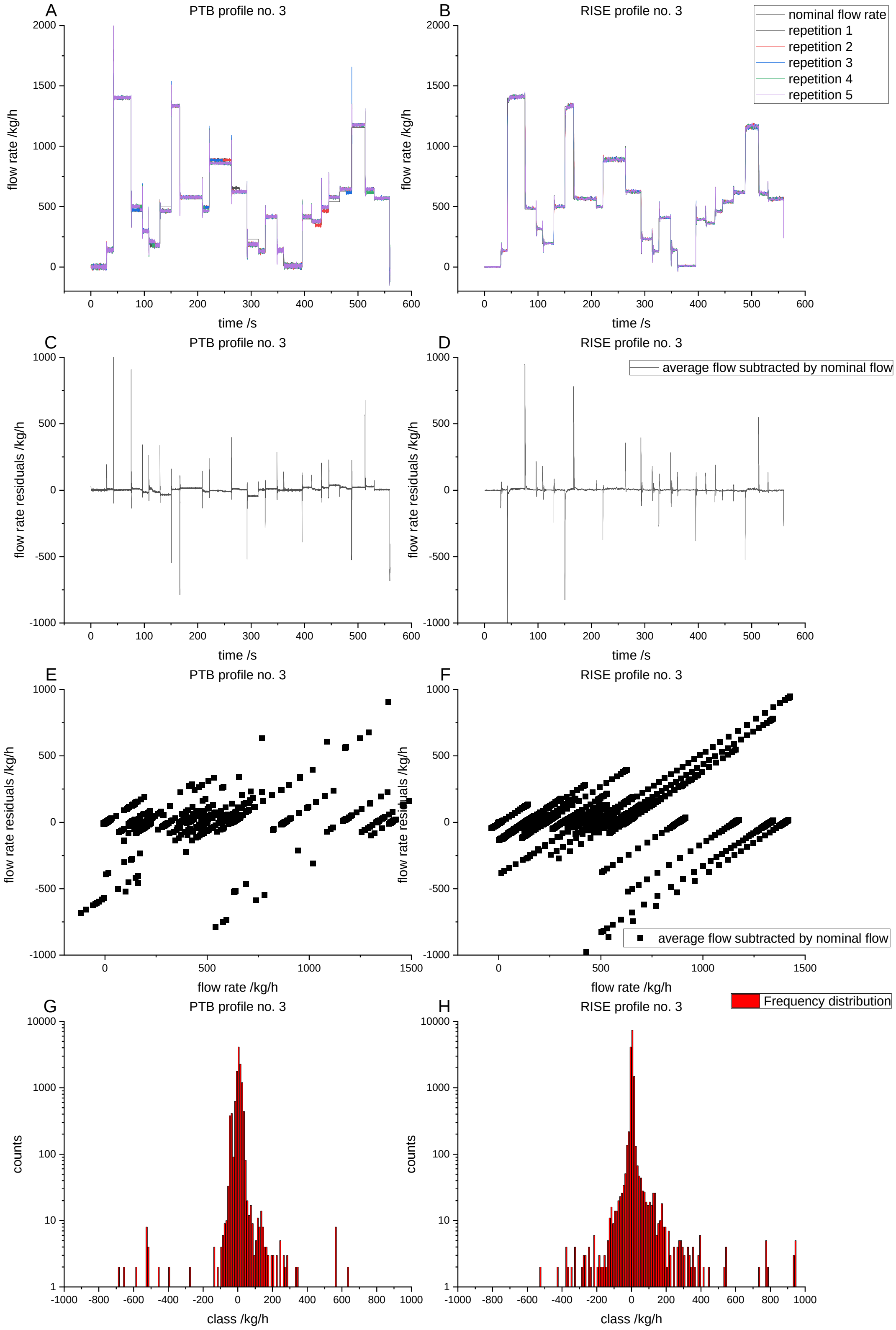


Figure 30: 1st row: continuous recorded (20 Hz) mass flow signal of the Coriolis from n profile repetitions; 2nd and 3rd row: Residuals of the averaged flow profile, plotted versus time and plotted versus flow rate (enlarged); 4th row: frequency distribution of the residuals. Each column represents measurements of one profile (no. 3) of one institute (PTB/RISE; Sub diagram heading).

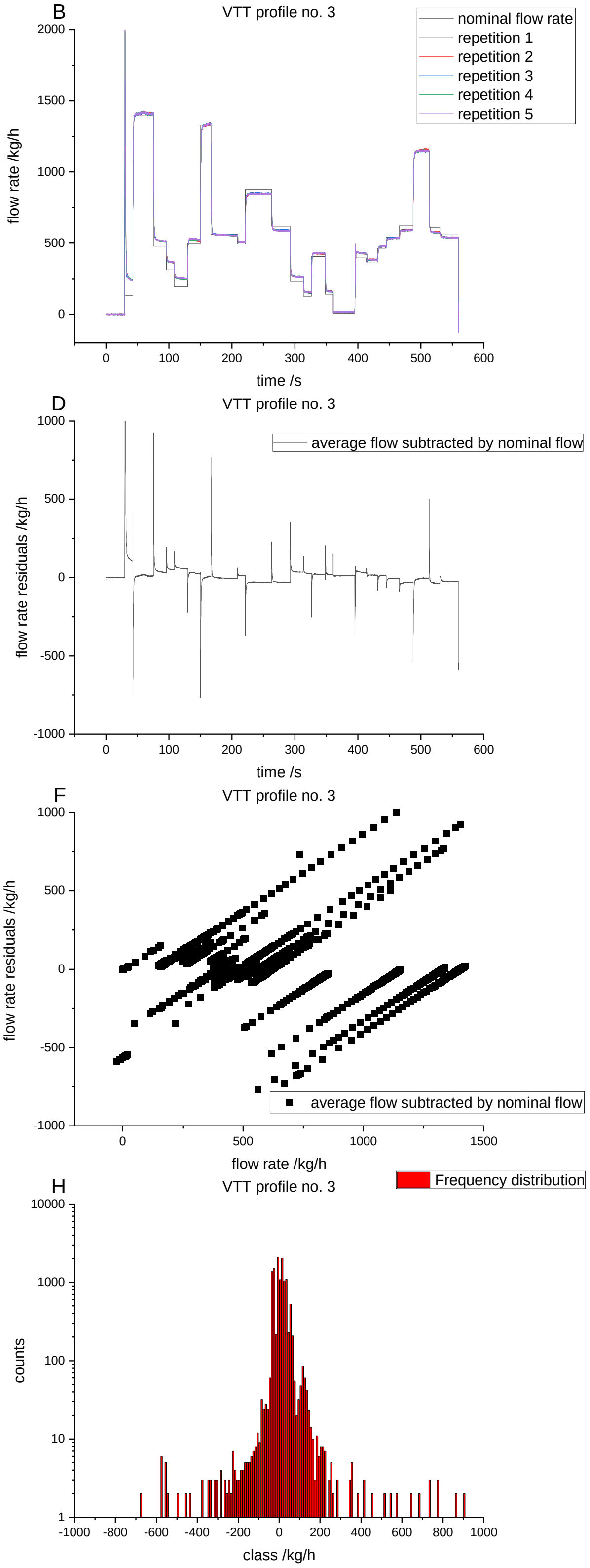


Figure 31: 1st row: continuous recorded (20 Hz) mass flow signal of the Coriolis from n profile repetitions; 2nd and 3rd row: Residuals of the averaged flow profile, plotted versus time and plotted versus flow rate (enlarged); 4th row: frequency distribution of the residuals. Each column represents measurements of one profile (no. 3) of one institute (VTT; Sub diagram heading).

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