

Comparison of Test Methods for Measuring Flow Stability

T. Meng^{1,2}, C. Koglin³, K. Richter³, T. Lederer³, C. Wang²

¹ Beihang University, mengt@nim.ac.cn, Beijing, P. R. China

² National Institute of Metrology, Beijing, P. R. China

³ Physikalisch-Technische Bundesanstalt, Berlin, Germany

Abstract: The technical quality of water flow facilities is defined by the quality of their pumps and valves, the methods used for creating a stable flow and the design of the pipeline layout; and it is directly reflected in the flow stability. However, using existing methods it is difficult to differentiate between the actual flow fluctuations and the flow meter's noise. The test results can be affected by the working principle, the sample rate and the response time of the flow meter used.

A turbine flow meter, a Coriolis flow meter, an electromagnetic flow meter, a clamp-on ultrasonic flow meter, a Laser Doppler Anemometry system and two types of pressure sensors were installed in series in the hot water flow facility of the PTB Berlin. A constant and a regular fluctuant flow were measured and monitored with these different meters at the same time.

The comparison of the test results reveal that among the flow meters the turbine flow meter has the highest actual sample rate and the fastest response time; however, its response time is still about 0.1s slower, when compared to the two types of pressure sensors. A good correlation was found between the results of the turbine meter and the Coriolis meter, demonstrating that the test results reflect the real flow fluctuation of the facility. An additional advantage of the use of the two types of pressure sensors is the ability to detect high frequency flow fluctuations.

1 Instruction

The technical quality of water flow facilities is defined by the quality of their pumps and valves, the methods used for creating a stable flow and the design of the pipeline layout; and it is directly reflected in the flow stability. However, using existing methods it is difficult to differentiate between the actual flow fluctuations and the flow meter's noise. In ISO9368^[1], a set of formulas is given to calculate the flow stability. These formulas - when applied to simulation data at a given amplitude, frequency fluctuation and noise -, did not effectively remove the noise from the flow meters.

As test results can be affected by the measurement principle, the sample rate and the response time of the test devices used, the selection of test devices is important. In order to determine the real flow stability, simultaneous measurements with devices using different measurement principles and subsequent correlation analysis is required.

2 Test system

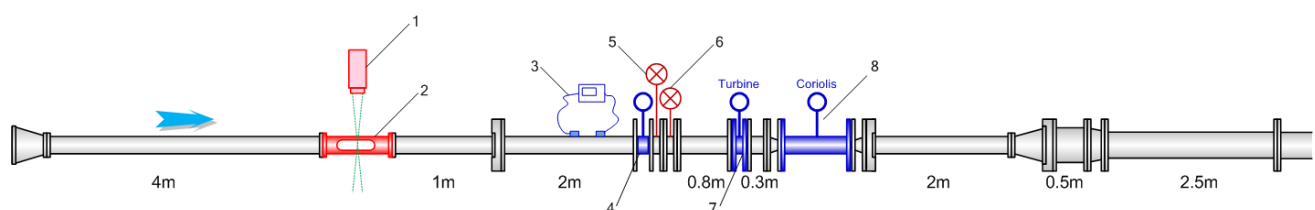


Figure 1: Test devices and pipe system

1- LDA; 2 - LDA chamber; 3- Clamp-on ultrasonic flow meter; 4 - EMF; 5 - P1, 6 - P2, 7 - TFM, 8 - CMF.

2.1 Flow measurement facility

All the tests were carried out at the heat meter calibration facility (in German W ärmez ählerprüfstrecke - WZP) of the 'Heat and Vacuum' department at PTB - Berlin. The WZP is a gravimetric measurement facility for calibration of flow meters. It operates between 3 m³/h and 1000 m³/h volumetric flow rate and a temperature from 3°C to 90 °C . The relative measurement uncertainty of the volume realisation amounts to 0.04% ($k = 2$)^[2,3].

In normal operation mode ('pump operation mode' ^[4]) the storage tank is in a state of overflow condition to keep the inlet pressure of the water supply pumps constant. A cyclone air separator tank located downstream of the pumps may also reduce the flow fluctuation as a buffer tank.

2.2 Test devices

The WZP has a more than 25 m long test section, which allows the installation of several test devices in series, as exemplified in Figure 1.

The test section, where the testing devices were installed, consists of pipes with a nominal diameter of DN 80. The first testing device installed in the test section is the Laser Doppler Anemometry (LDA) system (1, Figure 1). The DN 80 test chamber (2, Figure 1) was installed after 50 D (diameter) undisturbed inlet section.

As the LDA system, the clamp-on ultrasonic flow meter (UFM) (3, Figure 1) and the electromagnetic flow meter (EMF) (4, Figure 1) do not affect the flow profile they are installed upstream of the turbine flow meter (TFM). The Coriolis mass flow meter (CMF) (8, Figure 1) was installed downstream of all test devices, as CMF are less sensitive to disturbed flows. In addition a converging nozzle had to be used to reduce the diameter from DN 80 to DN 50 as the available device was a DN 50 Coriolis flow meter.

As flow fluctuations can lead to pressure changes in the pipe system, two types of pressure sensors were installed, P1 (5, Figure 1) and P2 (6, Figure 1). P1 is a dynamic pressure sensor designed to measure pressure perturbations in air or fluids in severe environments and small pressure disturbances on a much higher static head. It is a very sensitive and fast response sensor accomplishing a 'rise time' shorter than 9 μ s. P2 is a standard gage pressure sensor whose response time is less than 3 ms. The parameters of test devices are listed in Table 1.

Table 1: Parameters of test devices

| Device | D mm | Max flow m ³ /h | Output type | Output unit | Max output |
|--------|------|----------------------------|-------------|-------------|------------|
| TFM | 80 | 180 | Freq. | Hz | 680 |
| CMF | 50 | 180 | Freq. | Hz | 1000 |
| EMF | 80 | 180 | Freq. | Hz | 10000 |
| | | | Current | mA | 20 |
| UFM | 80 | 200 | Freq. | Hz | 1000 |
| P1 | 80 | / | Voltage | V | 2.5 |
| P2 | 80 | / | Current | mA | 20 |
| LDA | 80 | / | Data | / | / |

2.3 Data acquisition devices

Two data acquisition cards in use were made by National Instrument (NI). All frequency output signals were measured by PXI-6608 that was an 8 channels 32-bit counter, and PXI-6052 was used for analog signals. A LabVIEW program was developed to control synchronous acquisition from test devices, and it can also save and analyse test result. Its interface of test was shown in Figure 2.

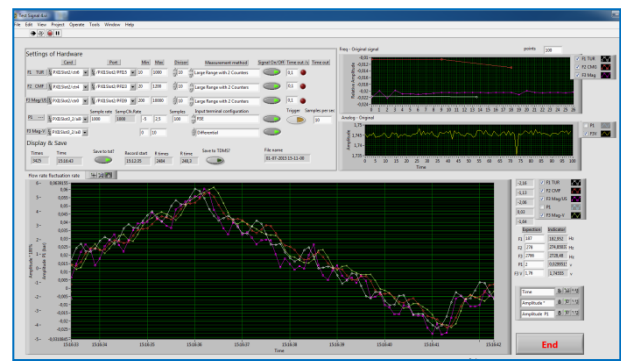
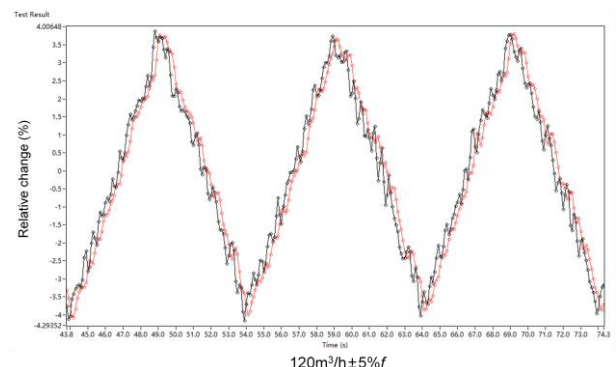


Figure 2: Interface of test program

The data of the LDA system was collected separately. The average sample rate was about 70Hz.

3 Flow stability test procedure

Based on the optimum working range of the flow meters, the stability test flow was carried out at two flow rates: 50m³/h and 120m³/h. In order to compare the response time of these test devices, regular fluctuation flow experiments, obtained by uniform change of the pump frequency, were carried out (Figure 3).



black line: TFM; red line: CMF

Figure 3: Output of TFM and CMF in a regular fluctuation test

In Figure 3 the flow rate was set to 120m³/h, then the frequency of the pump was adjusted by $\pm 5\%$ in form of a triangular function with a period of 10 s.

4 Output signals characteristic of test devices

4.1 Frequency output of the TFM

Every point in Figure 4 is a frequency value for a pulse of the TFM, which means instantaneous flow rate. The frequency value is approximately 187 Hz at 50 m³/h. It is easy to detect periodicity changes of the frequency of the pulses accumulating to ten points, which are linked to the ten blades of TFM (Figure 5).

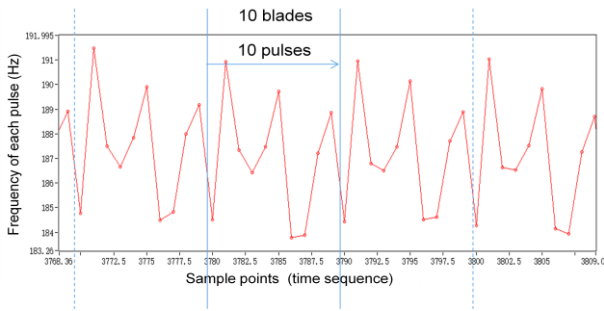


Figure 4: Frequency output of the TFM



Figure 5: Blades of the TFM

Therefore, the average value of every 10th frequency peak was analysed in order to reduce the effect of blades on flow stability.

4.2 Frequency output of the CMF

The shape of the frequency output of CMF consists of plateaus/steps of constant values (Figure 6). The value is nearly equal at one 'step' showing a width of about 0.1s at different flow rates, which means that new values of flow rate can be outputted each 0.1s.

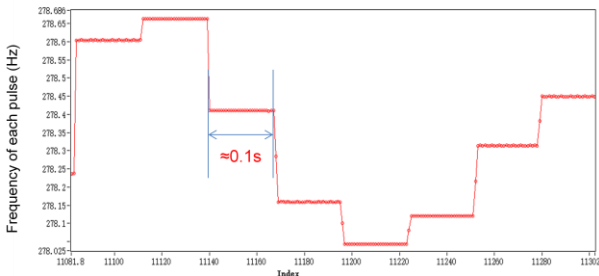


Figure 6: Frequency output of the CMF

Therefore, 10Hz is the fastest sample rate of instantaneous flow rate from CMF, which is much lower than its frequency output of approximately 287Hz at 50m³/h. And the smallest value of 'time constant' set in this meter is 0.2s.

4.3 Frequency and current output of the EMF

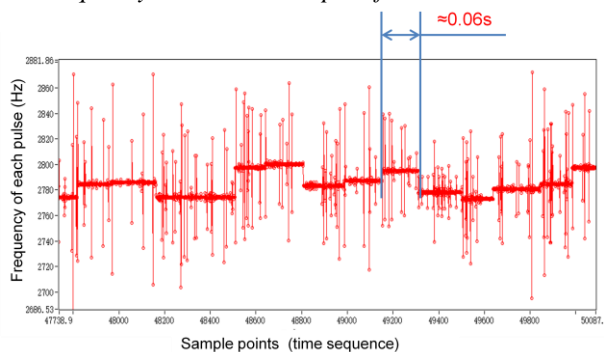


Figure 7: Frequency output of the EMF

The frequency output of EMF is similar to CMF's frequency output. The same 'steps' of constant frequency can be observed in Figure 7. The width of 'step' is about 0.06s which fits to the cycle of magnetic field polarity conversion of this EMF. It is noteworthy that the monitored signal quality is bad.

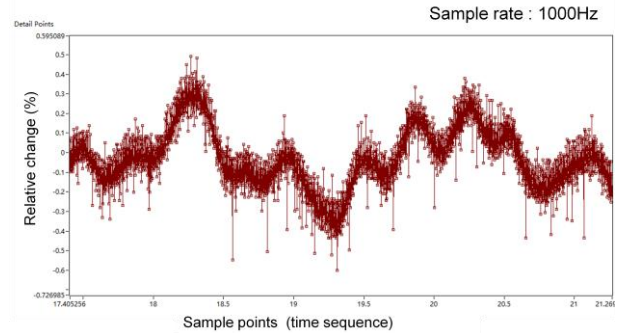


Figure 8: Current output of the EMF

The current output can be obtained at the same time with the frequency output, but the noise signal is still existent in Figure 8.

4.4 Analog output of pressure sensors

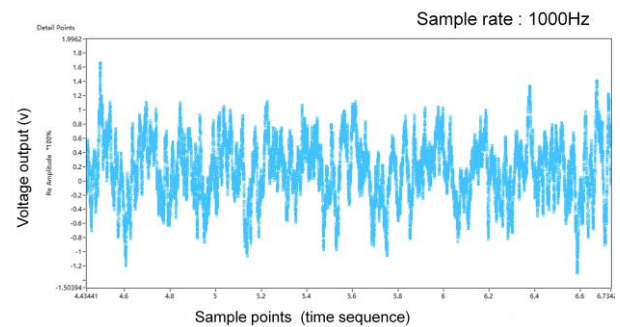


Figure 9: Voltage output of the P1

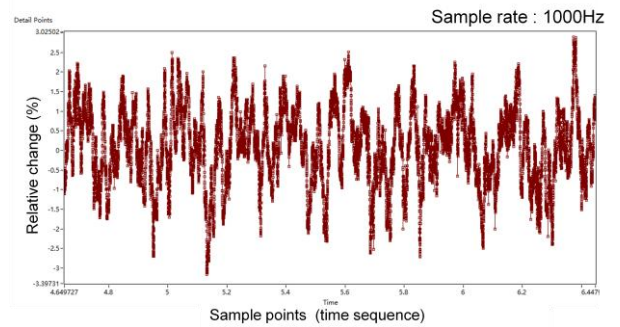


Figure 10: Voltage output of the P2

In the Figure 9 and Figure 10, a continuous signal can be obtained from the pressure sensors, and the sample rate depends on data acquisition devices. Normally, a sample rate of 1 kHz ~ 5 kHz was used in these tests.

4.5 Frequency output of the UFM

As shown in Figure 11, the 'steps' shape could also be observed in the output of UFM. This time a cycle consisted of one long step and 3 short steps. However, the width of step is very long, which means that the

UFM's response speed is too slow to observe the flow change.

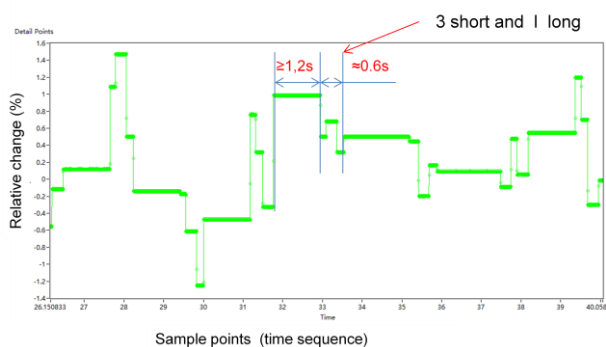


Figure 11: Frequency output of the UFM

4.6 LDA

The LDA only measures the fluid velocity of a very small region near the pipe centre, while the original velocity change is obtained directly. However, as shown in Figure 12, the fluctuation of LDA curve is acutely, and the amplitude is more than $\pm 5\%$. Even with 2s moving average filter, compared with the TFM, it still cannot clearly show the waveform that is regular fluctuation experiment of $50\text{m}^3/\text{h} \pm 1\%f$. That is mainly affected by turbulence. If the data rate of LDA could be increased to a value of 1000 Hz and a more effective filtering method was adopted, the system could be used for flow stability tests.

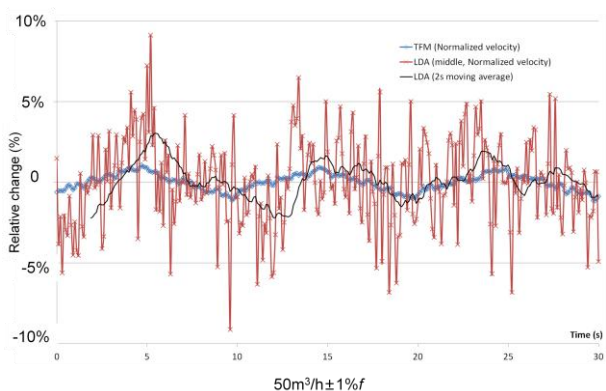


Figure 12: Comparison LDA with TFM in a fluctuation test

4.7 Comparison of test devices

Normally, a faster response speed and sample rate can be realized by applying a higher frequency output. However, the actual sample rate depends on the feature of output and principle of devices.

Table 2: Actual sample rate of test devices

| Flow rate m^3/h | Output frequency Hz | | Min sample period | Actual max sample rate Hz | | Min time constant |
|---------------------------------|---------------------|--------|-------------------|---------------------------|-------|-------------------|
| | 50 | 120 | | 50 | 120 | |
| TFM | 188.0 | 451.2 | 10 pluses | 18.8 | 45.12 | / |
| CMF | 277.8 | 666.7 | 0,1 s | 10.0 | | 0.2 |
| EMF(f)* | 2777.8 | 6666.7 | 0,06 s | 16.7 | | 0.0 |
| EMF(I)** | / | / | 0,06 s | 16.7 | | 0.1 |
| UFM | 250.0 | 600.0 | >1 s | 1.0 | | 1.0 |

* EMF (f) is the frequency output of EMF;

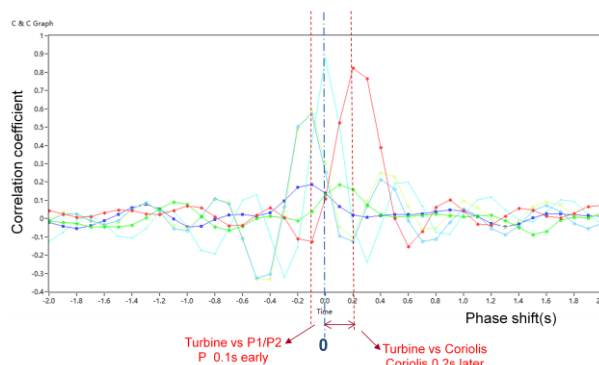
** EMF (I) is the current output of EMF.

As shown in Table 2, the TFM has the fastest sample rate of all flow meters, because the frequency output is its original signal. The other flow meters need a short time to do signal processing, calculation and conversion, which is why there are 'steps' in the output.

Actually, UFM and LDA just measure the fluid velocity at a small part in pipe, and flow rate was calculated based on repeated measurement and certain algorithm. Under test conditions, it is difficult to obtain real-time response to flow fluctuation from LDA and UFM, and therefore, they were not further analysed in the following data processing. Accordingly, the data of EMF is for reference only due to its poor signal quality.

5 Correlation analysis

In Figure 13, each curve is composed of correlation coefficients that were calculated at different phases between two devices. Here, one phase shift means that the time difference between data arrays of two devices is one minimum sampling interval. For example, if the point is at $x=0$, each data pair in the arrays of two devices is sampled at the same time. If x is equal to 0.1s for the curve of TFM-CMF, the sampling time of CMF's data is 0.1 s late compared to the TFM's at each pair of data arrays.



red line: TFM with CMF; bright green line: TFM with EMF;
 yellow line: TFM with P2; bright cerulean line: TFM with P1
 blue line: CMF with EMF; cerulean line: P1 with P2

Figure 13: Correlation coefficient curves of test devices

Some useful information can be obtained from Figure 13.

(1) A few pairs of devices have good relativity from the max value of curve at Y-axis. Since the two kinds of pressure sensors have high consistency, their correlation coefficients are always greater than 0.85 in all tests. This value of TFM and CMF is about 0.8 ~ 0.95. Good correlation proved that the flow fluctuation is mainly brought from the facility itself, rather than these devices. TFM or CMF with the pressure sensor also have a good correlation coefficient which is about 0.5 ~ 0.8. The pressure signals can be used to find and monitor the high frequency pulsation flow in the facility.

(2) We can also observe differences of response speed between test devices from the position of maximum correlation coefficient at X-axis. For instance, the peak value of the TFM-CMF curve appears at $x=0.2\text{s}$, which means the response speed of CMF is about 0.2 s late

compared to the TFM. The relationship of response speed between some different typical devices is shown in Table 3.

Table 3: Different of response speed between devices (Unit: s)

| Flow rate m ³ /h | 50 | 120 | 50 ±1%f | 50 ±5%f | 120 ±1%f | 120 ±5%f |
|--------------------------------|------|------|------------|------------|-------------|-------------|
| TFM - CMF | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 |
| TFM - P1 | -0.1 | -0.1 | -0.1 | -0.1 | -0.1 | -0.1 |
| TFM - EMF(f) | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| TFM - EMF(l) | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 |

The TFM has the highest and fastest response time of all examined flow meters. However, it is still about 0.1s slower than the pressure sensors. The delay of TFM could be coming from mechanical force, but that is more likely attributed to electronic reasons including signal conversion and algorithms for CMF and EMF. For example, the minimum 'time constant' that should be set in transducer of CMF is 0.2 s.

However, there is no obvious relationship between the delay and installation position of test devices. The delay is quite constant at different flow rates and test conditions. The tested fluctuation of flow rate is caused by the system's flow rate change, which means the change of flow rate and pressure happens almost simultaneously in the whole pipe system of the flow facility rather than being transmitted from upstream to downstream.

6 Discussion of method for calculating flow stability

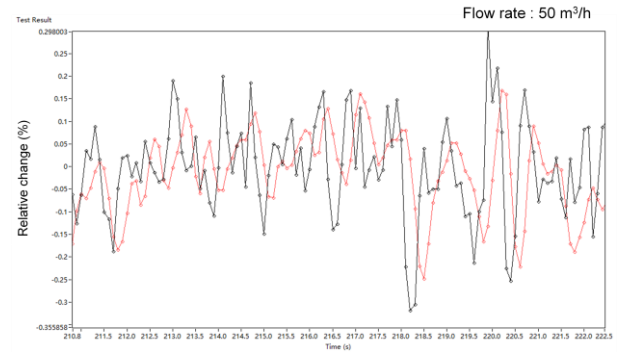
The test data of TFM and CMF was used to calculate flow stability because of the good correlation both devices showed. Firstly, Bessel formula was used to calculate the standard deviation of TFM and CMF test results. A set of comparative data of is shown in Table 4 and 5. Concerning the standard deviation value, at these two flow rates, TFM is always slightly larger than CMF. It can also be seen in the output curves of flow meters (Figure 14). The curve of CMF lags behind TFM and is smoother; this is mainly caused by the effect of 'time constant', which decreases the sensitivity of flow changes. In order to check this conclusion, a new set of moving average data was calculated from raw data of TFM every 0.2 s to simulate damping of CMF. The standard deviation of CMF and the simulation data are very close, showing that the change of correlation coefficients, relativity between two flow meters becomes better. Therefore, the experimental data of TFM can reflect the fluctuation of flow facilities more accurately. Finally, in this experiment, the standard deviation of TFM is used as the result of flow stability of facility.

Table 4: Test result comparison between TFM and CMF at 50m³/h

| Data source | TFM (real time) | CMF (time constant =0.2s) | TFM (simulation time constant =0.2s) |
|-------------------------|-----------------|---------------------------|--------------------------------------|
| Standard deviation | 0.132% | 0.110% | 0.109% |
| Correlation coefficient | 0.854 | | 0.909 |

Table 5: Test result comparison between TFM and CMF at 120m³/h

| Data source | TFM (real time) | CMF (time constant =0.2s) | TFM (simulation time constant =0.2s) |
|-------------------------|-----------------|---------------------------|--------------------------------------|
| Standard deviation | 0.188% | 0.141% | 0.137% |
| Correlation coefficient | 0.863 | | 0.945 |



black line: TFM; red line: CMF

Figure 14: The relationship of TFM and CMF in a same test

Within two months, as shown in Table 7, no less than 10 experiments were done at each flow rate, while each test took 5 to 20 minutes. The experimental results show a very good consistency and repeatability respectively as low as 0.004 % and 0.009 %. Because self-collection data processing method wasn't used, the above calculation result is stricter relative to the method in ISO 9368. In reference [5], the fluctuation of system and flow meter's self noise were separated by a correlation coefficient that was used as weight coefficient, but because there was no reasonable mathematical provenance to evaluate its applicability, in this paper it was also not in use. It was difficult to convert flow stability from pressure change, so the data of pressure was also not used.

Table 6: Result summary of flow stability test

| No. | Standard deviation from TFM | |
|---------|-----------------------------|----------------------|
| | 50m ³ /h | 120m ³ /h |
| 1 | 0.134% | 0.202% |
| 2 | 0.134% | 0.196% |
| 3 | 0.132% | 0.190% |
| 4 | 0.131% | 0.197% |
| 5 | 0.130% | 0.180% |
| 6 | 0.127% | 0.176% |
| 7 | 0.130% | 0.201% |
| 8 | 0.122% | 0.196% |
| 9 | 0.123% | 0.183% |
| 10 | 0.125% | 0.195% |
| 11 | 0.131% | / |
| Average | 0.129% | 0.192% |

7 Conclusion

In summary, TFM is the best choice for the flow stability test. The very good relativity between TFM and CMF proved that the measurement results can reflect the fluctuation of flow facility.

Although it is not directly used for the calculation of flow stability, pressure sensor can be used for analysis and monitoring the high frequency fluctuation in flow facilities, which can compensate that actual sample rate of flow meter is low.

In our test, the best combination of flow stability test devices is: TFM and CMF, as well as one pressure sensor with high response speed. CMF can also be left out when the performance of TFM is accepted.

If the data rate of LDA can be enhanced by providing the particle concentration or other means, the effect from turbulence can be reduced, its measurement result is also worth looking forward to.

Acknowledgements

The support provided and discussions with colleagues from working group 7.52 of PTB are appreciated. Financial support for this study was also provided by Chinese National Public Benefit (Quality Inspection) Research Foundation (Grant No. 201510003).

References

- [1] ISO 9368-1: *Measurement of liquid flow in closed conduits by the weighing method – Procedures for checking installations – Part 1: Static weighing systems*, 1990.
- [2] K. Tawackoliana, O. Bükera, J. Hogendoornb, *et al.*, Calibration of an ultrasonic flow meter for hot water, *Flow Measurement and Instrumentation*, **Vol 30**, 166-173, 2013.
- [3] T. Ledderer, N. Mathies, J. Rose, *et al.*, New Test Facility for Large Water Flowrates Up To 1000 m³/h in a Temperature Range Between 3°C and 90°C at PTB- Berlin, in *Flomeko2009*, 2009.
- [4] N. Mathies, J. Rose, T. Ledderer, New Measurement Facility for Heat and Cold Meters at the PTB, *Euro Heat & Power English Edition*, **Vol. 34V**, 52-56, 2006.
- [5] J. S. Paik, K. B. Lee, P. Lau, *et al.*, Final report on CCM.FF-K1 for water, *Metrologia*, Vol. 44, Tech. Suppl. 07005, 2007