Design and experimental analysis of transfer standard in water flow comparison

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Abstract

The design of transfer standard is one of the most important factors of the success of comparison. 13 legal metrology laboratories participated in the recent Chinese water flow standard facility comparison. The transfer standard consisted of a velocity flowmeter transfer standard package (TSP) and a Coriolis mass flowmeter TSP were designed by the pilot laboratory. The velocity flowmeter TSP included one turbine flowmeter and one electromagnetic flowmeter which were assembled in series, and two types of flowmeter with different principle played a complementary role to ensure the reliability of the transfer standard. The mass flowmeter TSP can be tested on different calibration systems in one laboratory by special pipes designed, which supported a laboratory internal comparison. The double packages transfer standard provided a lot of wealth of information for comparison result analysis. It was also found that some participated facilities had deficiencies like bad water quality and leak of diverter. The experimental analysis of TSPs helped these laboratories to improve their facilities.

Key word: Comparison**;** Transfer standard; Water flow facility; Turbine flowmeter; Coriolis mass flowmeter.

1 Introduction

Comparison is one of the main techniques for inspecting whether the measurement values of the facilities are uniform. Transfer standard is the medium for conducting comparison. The design of transfer standard is an important work of the comparison activity to affect the analysis of experiment data and result.

Flowmeters are not only the device under tested of flow facilities, but also the first choice for transfer standard. In the early water flow comparison, orifice flowmeter was commonly utilized as the transfer standard meter, for example, comparison piloted by NEL of UK and 5 national metrology laboratories participated in the early 1980s [1], and a water flow comparison of 4 laboratories was organized in the Asia-Pacific Region in the 1990s [2]. In recent years, with the improvement of machining and electronic manufacturing, more and more flowmeters with higher accuracy and repeatability are becoming the alternatives of transfer standard meter. For instance, the turbine flowmeter has been utilized in many international key comparisons. Moreover, the PTB of Germany has installed turbine flowmeters which are used in comparison between gravimetric method standard and the pipe prover in their water flow facility [3]. Besides, the Coriolis mass flowmeter has been used in the key comparison (APMP.M.FF-K1) in 2009 [4].

To improve the reliability and availability, transfer standard is often designed as a package which consists of two or more flowmeters. It also includes upstream and downstream straight pipe and flow conditioner besides flowmeters. NEL designed a transfer package that included two orifice flowmeters in a series connection in the inter-comparison mentioned above. A double turbine flowmeters transfer package was used in water comparison of CENAM, PTB and NIST [5]. More information can be acquired from Multi-meters transfer package than single flowmeter transfer standard, which is an important reference for comparison result analysis.

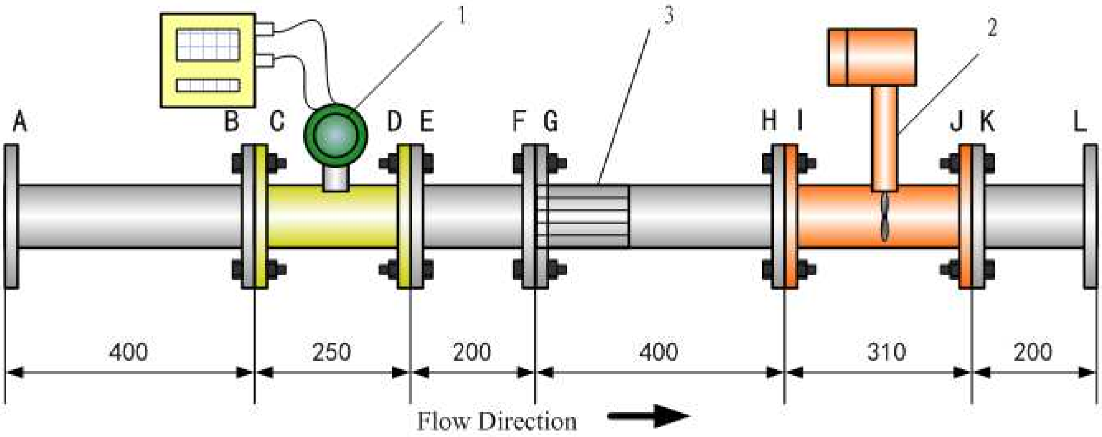
During 2008-2010, a national water flow comparison had been performed in China. NIM (National Institute of Metrology) was the pilot laboratory, and 13 provincial metrology institutes participated. Uncertainty of these facilities are all better or equal to 0.1% (k=2). The pilot laboratory has designed a transfer standard made up of two transfer standard packages: velocity flowmeter package and the mass flowmeter package.

2 Design of Transfer Standard Package (TSP)

2.1 TSP of Velocity Flowmeter (TSP-1)

Pipe diameter of TSP-1 is 100mm. It is comprised of two velocity flowmeters connected in series. As shown in Figure

1, the electromagnetic flowmeter is located in the upstream, and the turbine flowmeter is installed in the downstream. Both of them are equipped with an upstream pipe with 4 times length of diameter (*D*) and a downstream pipe of twice length of *D*. A grid type flow conditioner is equipped in the upstream pipe of turbine flowmeter. For convenience of transportation, the whole TSP can be divided into two parts at flange F and G. Every flowmeter and its upstream and downstream pipes are taken as one unit to package and transport. Locating pins are designed at flange F and G in order to ensure the consistency of installation.



1. Electromagnetic flowmeter; 2. Flow conditioner; 3. Turbine flowmeter.

Figure 1 Schematic of TSP-1 (Unit: mm)

Unlike common usage that two same type flowmeters are connected in series, TSP-1 includes two flowmeters with different principles. Usually turbine flowmeter has good repeatability, for example, the repeatability of the turbine flowmeter used in TSP-1 is better than 0.02%. Its output is digital pulse singles with good anti-jamming performance and without zero drift, so it is often used as transfer standard flowmeter. But it greatly is affected by velocity distribution distortion of inlet flow and swirl flow [6]. Besides, it is easier dirtied by the solid impurities in the measuring medium. Consequently, its mechanical performance would be influenced, and drift produced, which are adverse effects to the comparison experiment. The mechanical structure of electromagnetic flowmeter is simple. The measuring tube has no movable component, and is suitable for fluid with low cleanness. It has a relatively good repeatability, which can reach 0.05%~0.1%. However, its long-term stability, with the possibility of zero drift, is not so satisfactory. According to the features of the two flowmeters, the turbine flowmeter is selected as primary transfer meter. The electromagnetic flowmeter and pipes, of which inner wall machined are tight fit, form the front straight pipe of the turbine flowmeter. With the flow conditioner, it can improve and keep fluid flow regime stable at the entrance of turbine flowmeter. Based on well repeatability and short-term stability of electromagnetic flowmeter, the drift of the turbine flowmeter could be effectively monitored. It functions as the monitoring flowmeter. Thus advantages of each flowmeter in TSP-1 can be fully utilized, while the defect of any flowmeter is compensated for in principle.

2.2 TSP of Mass Flowmeter (TSP-2)

TSP- 2 is composed of a DN50 Coriolis mass flowmeter and connection pipes. Two DN50 pipes with a length of 250mm (5*D*) are respectively installed at upstream and downstream of the flowmeter. Both ends of the TSP-2 can be equipped with DN50-DN100 reducers. TSP-2 can be installed on DN50 test bench or DN100 test bench by means of the pair of reducers. The Locating pins, same as at flange F and G, are designed at flange N, O, T and U for reinstallation.

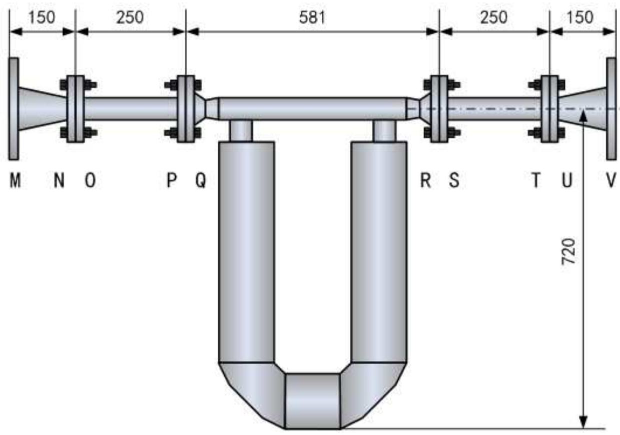


Figure 2 Schematic of TSP-2 (Unit: mm)

Mass flowmeter is a high-accuracy flowmeter with rapid development in recent years. Some manufactories claim that their product accuracy would be better than ±0.05%. It also has the advantages of high repeatability and stability to satisfy the requirements as a transfer standard meter. However, bigger size mass flowmeters, like diameter of DN80 or above, are so large and so heavy. It is difficult to be assemble in transfer package, and inconvenient to transport and install. In the international key comparison of BIPM.CCM.FF-K1 [7], [8], a DN100 turbine in series connection with mass flowmeter was utilized, and the length of TSP reached 3.36m. But in the APMP.M.FF-K1, only one meter of this TSP was retained that based on the consideration of the length of installation and transportation. The size of the DN50 mass flowmeter used in TSP-2 is relatively small. It is not difficult for the participant of comparison to transport and install.

It is an important characteristic that mass flowmeter is less affected by turbulent flow. Usually, there are no requirements on the lengths of front and back straight pipes. Based on this feature, TSP-2 is designed to test the error between the two standard systems (DN 100 and DN 50 test benches) of each participating laboratory. Different from TSP-1 used as primary transfer standard, TSP-2 is defined as supplementary transfer standard.

3 Comparison Experiment

According to the equipment conditions and characteristics of TSP, the comparison experiment is designed as shown in Table 1. Five flow rates are included in all. For the purpose of limiting the volume of experiment, there are at most 3 flow rates for every TSP on each test bench.

Table1 Test point of comparison

Flow rate(m^3/h)	**160**	**80**	**50**	**30**	**20**	**TSP**
DN100 Test bench	√	√	√	-	-	TSP-1
	-	-	√	√	√	TSP-2
DN50 Test bench	-	-	-	√	√	

Note: "√" and "-" denote the test flow rates and non-experimental points, respectively.

The measured quantities are the K-factors of 3 flowmeters, which are $K_{v,T}$ (turbine flowmeter), $K_{v,E}$ (electromagnetic flowmeter) and K_m (mass flowmeter). For the uncertainty of participants' facilities are close, reference values are calculated by weighted average method [9] which has been agreed in the protocol. The comparison result is judged by E_n value [10] which is computed as Formula (1) at every flow rate of each flowmeter:

$$E_n = \frac{|y_{ref} - y_i|}{k \cdot u_{d,i}} \times 100\% \quad (1)$$

where y_i denotes the test result of the i-th laboratory; y_{ref} denotes the reference value of a single flow rate of each flowmeter; k is the cover factor, in this comparison, k=2; $u_{d,i}$ is the standard uncertainty of $(y_{ref} - y_i)$, expressed by Formula (2):

$$u_{d,i} = \sqrt{u_{ref}^2 + u_i^2 + u_e^2} \quad (2)$$

where U_{ref} is the standard uncertainty of reference value; U_i is the standard uncertainty of the result measured by the i-th lab; U_e is the stability of transfer standard.

The design of TSP and comparison experiment supplements each other. Two sets of TSPs can be used in separate comparison experiment. Meanwhile more abundant information can be gained through the relationship of two TSPs' experiments in the comparison result analysis. TSP-1 is used to compare the participating laboratories in horizontal, and the purpose of TSP-2 focus on vertical that means to check up different test benches in same laboratory. The flow rate, 50m^3/h, is the crossing that becomes the relationship of different experiments. On the other hand, the density measurement is included in this comparison. Because the types of flowmeters are different, the density of water need be tested whatever the gravimetric or volumetric method facilities they are.

4 Performance Test of TSPs

4.1 Installation Effect

Parts of both TSPs have to be dismounted in transportation as described above. In this experiment, both TSPs are tested before and after they are repacked and reinstalled. It checks up the effect of reassembling and reinstallation through comparing the change of K-factor. Experimental result of TSP-1 is shown in Table 2:

Table 2 Comparison of $K_{v,T}$ before and after reassembling and reinstallation

Flow rate (m^3/h)	$K_{v,T}$ (L^{-1}) Before	After	Relative deviation
160	12.843	12.845	-0.016%
80	12.855	12.853	0.016%
50	12.877	12.876	0.008%

Because only the two reducers of TSP-2 need to be dismounted, the test is done at the DN100 test bench. The test result is shown in Table 3:

Table 3 Comparison of K_m before and after reassembling and reinstallation

Flow rate (m^3/h)	K_m (kg^{-1}) Before	After	Relative deviation
50	360.07	360.07	-0.001%
20	360.09	360.08	0.003%

The data in Table 2 and 3 shows that the relative changes of K-factor do not exceed 0.02%. Thus, it is suggested that the installation effect would be very limited for the comparison results. In addition, the short-term stability of TSPs is also good.

4.2 Installation Directions

Because the body of mass flowmeter is high, some laboratories cannot install it normally (body straight down). Manufacturer advises that the meter body can be horizontally or standing upside down for installation. Drawing of installation is shown as Figure 3:

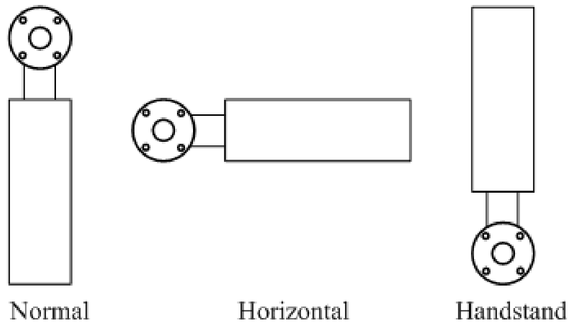


Figure 3 Different Installation Directions of Mass Flowmeter

Three installation directions are tested respectively by the pilot laboratory, and the results are shown in Figure 4:

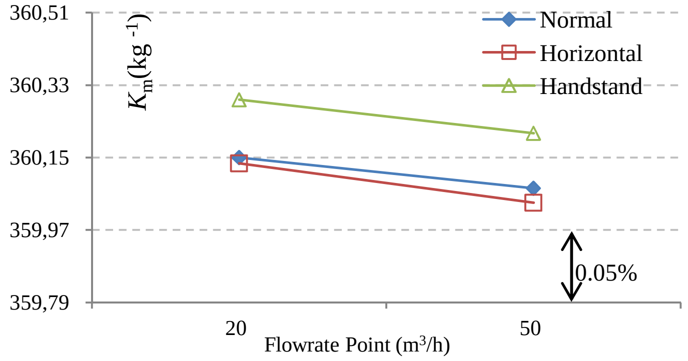


Figure 4 K_m at different installation directions

Experimental results show that the difference between horizontal installation and normal installation is small and less than 0.02%. However, headstand installation would have a relatively bigger influence. This result has been explained to each participant before starting the comparison and written in the protocol.

4.3 Different Pipe Pressures

Working pressure of water flow facilities in comparison is different. Moreover, measurement performance of mass flowmeter would be influenced as well under different pipe pressures. The manual of flowmeter shows that the change rate of K-factor is about -0.012%/bar with pressure rising. The mass flowmeter is tested under pressure of 0.2MPa and 0.4MPa respectively, and the values at the flow rates are 50 m^3/h and 20m^3/h, respectively. The experimental results are shown as Table 4:

Table 4 Experimental Results under Different Pipe Pressures

Flow rate (m^3/h)	K_m (kg^{-1}) 0.2 (MPa)	0.4 (MPa)	Relative deviation
50	360.07	360.04	0.010%
20	360.15	360.05	0.028%

At 20m^3/h, the variation of K-factor with experimental pressure is close to the one that is described in the manual. But at 50m^3/h, the change is less. The pressure correction should be taken into account when reference values are calculated.

4.4 Stability of TSPs

Stability is the most important performance of transfer standard, as it directly determines the success of the comparison. Before comparison, the TSPs would be repeatedly tested by the pilot laboratory. In addition, a petal-like comparison route (Figure 5) is adopted. After each small size loop, the TSPs would also be retested to check its stability by the pilot laboratory.

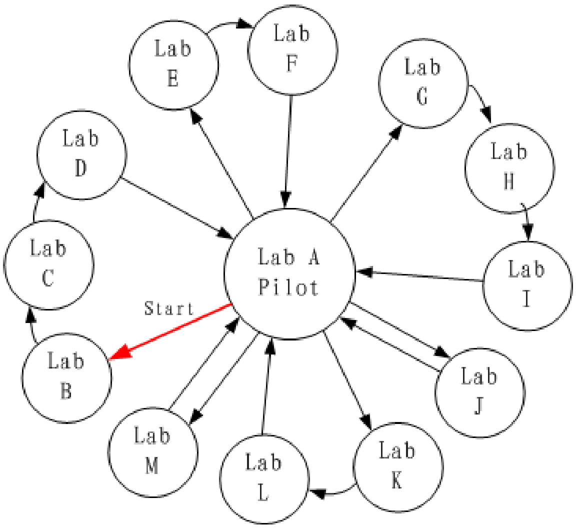


Figure 5 Comparison Route

TSP-1 and TSP-2 were tested for 11 times and 9 times respectively. Experimental results are shown as Figure 6 ~ 8. The horizontal coordinate denotes the sequence number experiment, and vertical coordinate denotes the relative deviation, d_r, between the result of a single experiment and the average value (Formula 3).

$$d_r = \frac{K - \overline{K}}{\overline{K}} \times 100\% \qquad (3)$$

where K is the result of a single experiment, and $\overline{K}$ shows the average value of all retests.

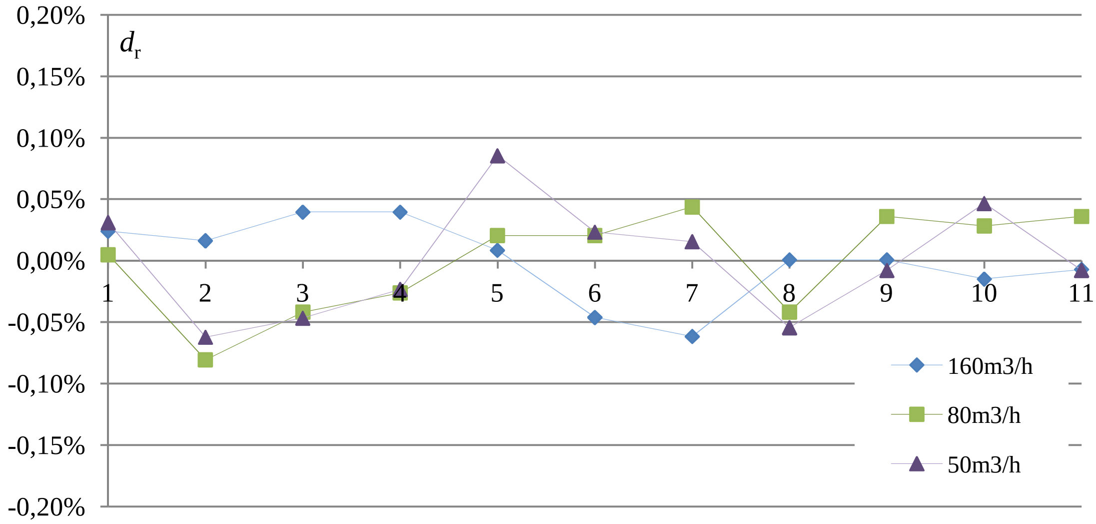


Figure 6 Stability test of turbine flowmeter

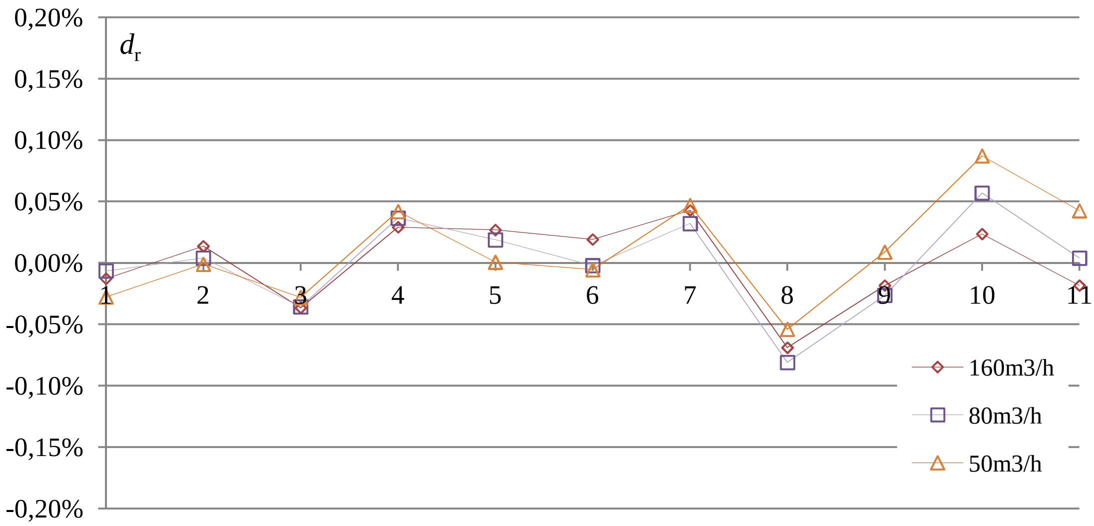


Figure 7 Stability test of electromagnetic flowmeter

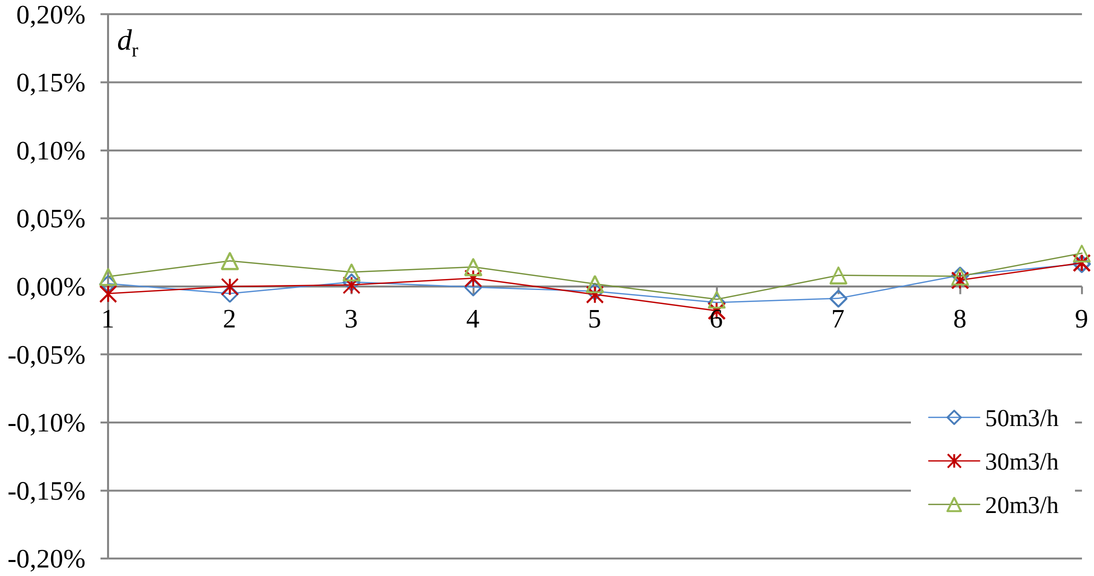


Figure 7 Stability test of mass flowmeter

The relative standard deviation of all retest data of each flowmeter is used as the stability at each flow rate. It is included in the computation of E_n value, which is given in Formula (1) and (2). Stabilities of two flowmeters in TSP-1 are close, and both of them are better than 0.05%. In Figure 7 of electromagnetic flowmeter, a strong correlation is indicated between 3 trend curves of K-factors at different flowrate, which would suggest the drift occurred. But the correlation of turbine flowmeter is unobvious. Furthermore, since the changes of two flowmeters K-factor do not show apparent correlation, the unsteadiness which occurs due to the drift of pilot laboratory facility is rejected in the computation of stability like the reference [7]. Stability of the mass flowmeter of TSP-2 is better than that of TSP-1. It is superior to 0.01%, and the maximum deviation from average value is less than ±0.02% in 9 groups of data.

5 Analysis

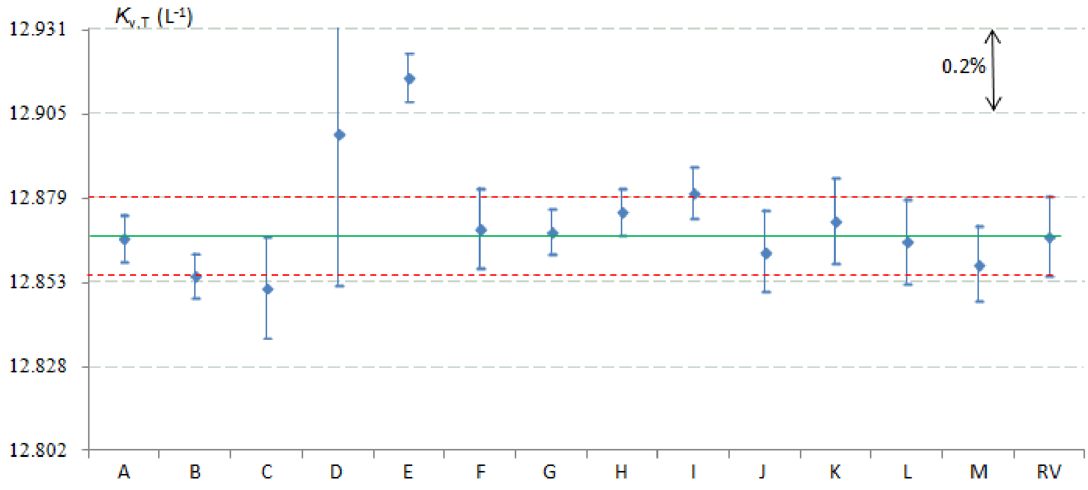
These two sets of TSPs were tested on water flow facilities of 13 laboratories in China in two years. Some problems in these facilities or in experiments have been found when the comparison result was analyzed.

5.1 Comparison Result Analysis with TSP-1

In the comparison results of turbine flowmeters, the E_n values at various flowrate in lab E are significantly greater than 1, and its results are shown in Table 5. The deviation of the comparison results from the reference values is shown in Figure 9 (the distributions of data at 3 flow rates are similar; only the case of 50m^3/h is illustrated as an example).

Table 5 Lab E's test results of turbine flowmeter

Flow Rate (m^3/h)	**160**	**80**	**50**
Lab E, $K_{v,T}$,(L^{-1})	12.875	12.880	12.916
Reference Values, $K_{v,T}$,(L^{-1})	12.843	12.848	12.868
Relative Deviation	0.25%	0.25%	0.38%
E_n	***2.85***	***2.45***	***3.42***



Note: Letters on the horizontal axis is the codes of laboratories; RV denotes reference value.

Figure 9 Comparison results of turbine flowmeter (50m^3/h)

However, the different conclusion is obtained from the result of the electromagnetic flowmeter tested as the same time with turbine flowmeter, as shown in Table 6. The E_n values of this laboratory are all less than 1 at 3 flow rate, and the result are all within the equivalent lines as shown in Figure 10. Moreover, comparison results of TSP-2 are referred to distinguish the reason of difference in TSP-1. In TSP-2 comparison, the E_n value of Lab E is only 0.02 at 50m^3/h, and the result is shown in Figure 11, which is similar to the result of electromagnetic flowmeter.

Table 6 Lab E's test results of electromagnetic flowmeter

Flow Rate (m^3/h)	**160**	**80**	**50**
Lab E, $K_{v,E}$,(L^{-1})	181.288	181.323	181.323
Reference Values, $K_{v,E}$,(L^{-1})	181.211	181.232	181.248
Relative Deviation	0.04%	0.05%	0.04%
E_n	**0.47**	**0.5**	**0.41**

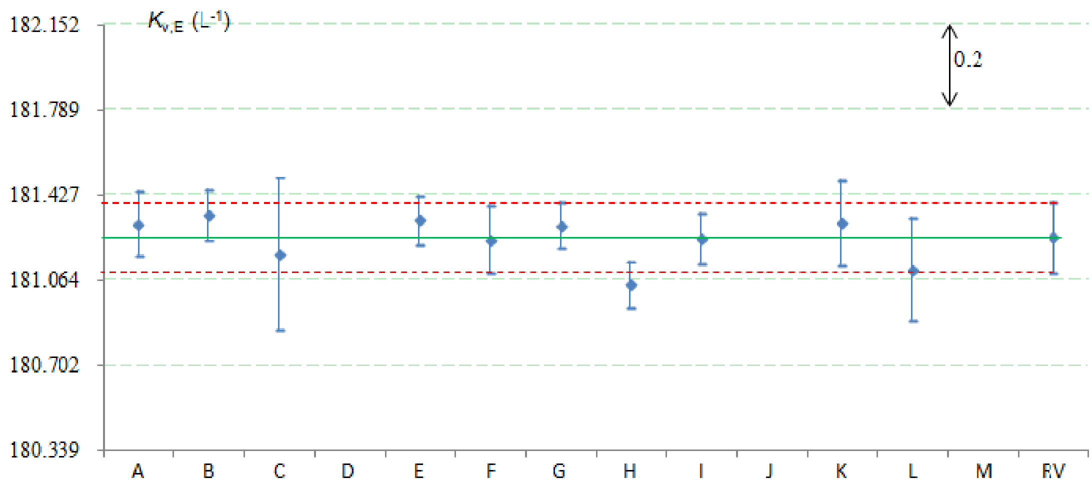


Figure 10 Comparison results of electromagnetic flowmeter (50m^3/h)

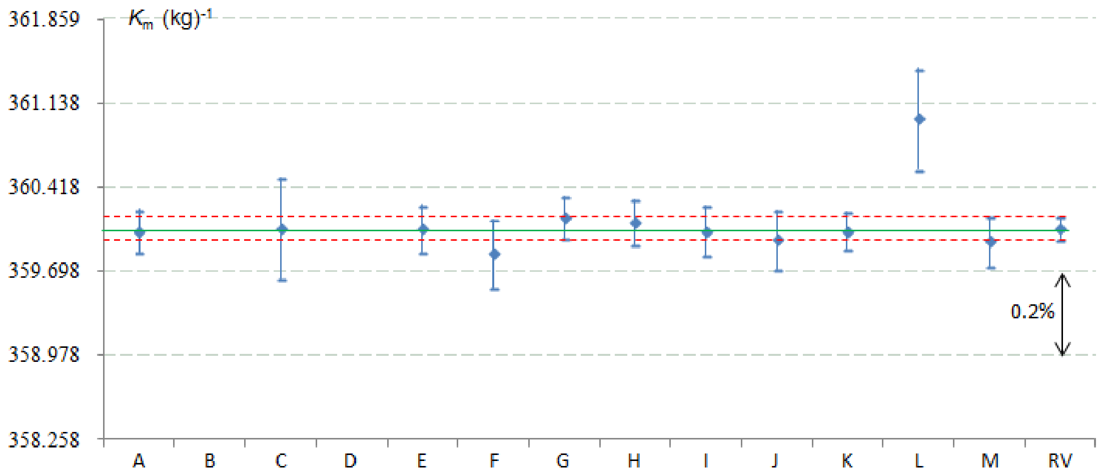


Figure 11 Comparison results of TSP-2 (50m^3/h, test bench of DN100)

Summarizing the result above, the focus is on the turbine meter: whether it is dirtied in the experiment. For further analysis of the reason of deviating primary reference values, original data of lab E is referred. Lab E had done several groups of experiments in which included some auxiliary experiments on TSP-1. It is found that the K-factor of turbine meter substantially fluctuate in the different groups (see Figure 12). The maximum change is about 0.5%, much greater than the stability (0.05%) of the turbine flowmeter measured by the pilot laboratory. Meanwhile, data of the electromagnetic flowmeter remain relatively stable, as shown in Figure 13. Its fluctuation in several experiments is about 0.1%, which is similar to the results from other laboratories. Therefore, it can be deduced that the turbine flowmeter had been polluted by impurities in the water during the experiment, and drift occurred.

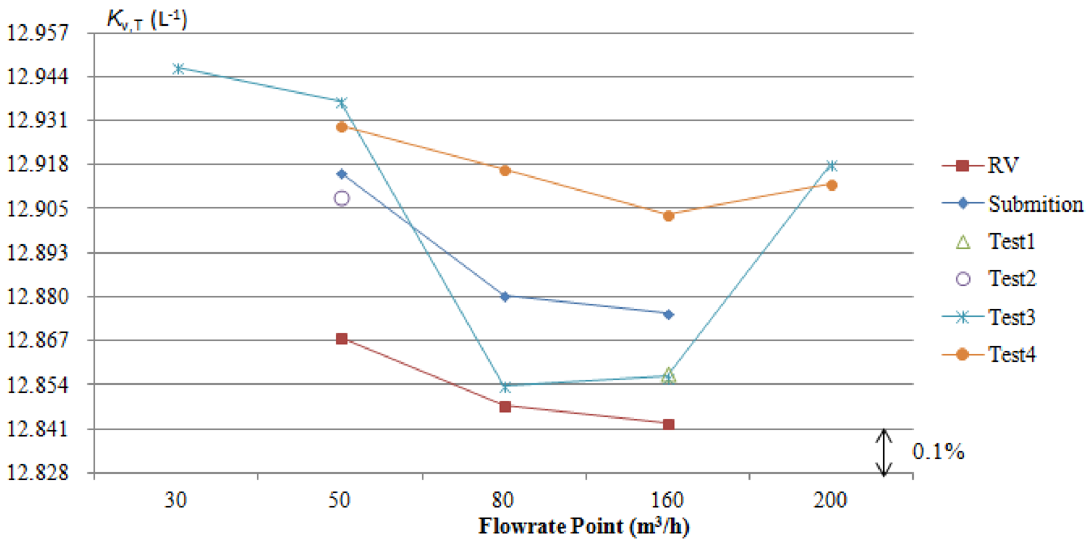


Figure 12 Summarization of data of the turbine flowmeter at lab E

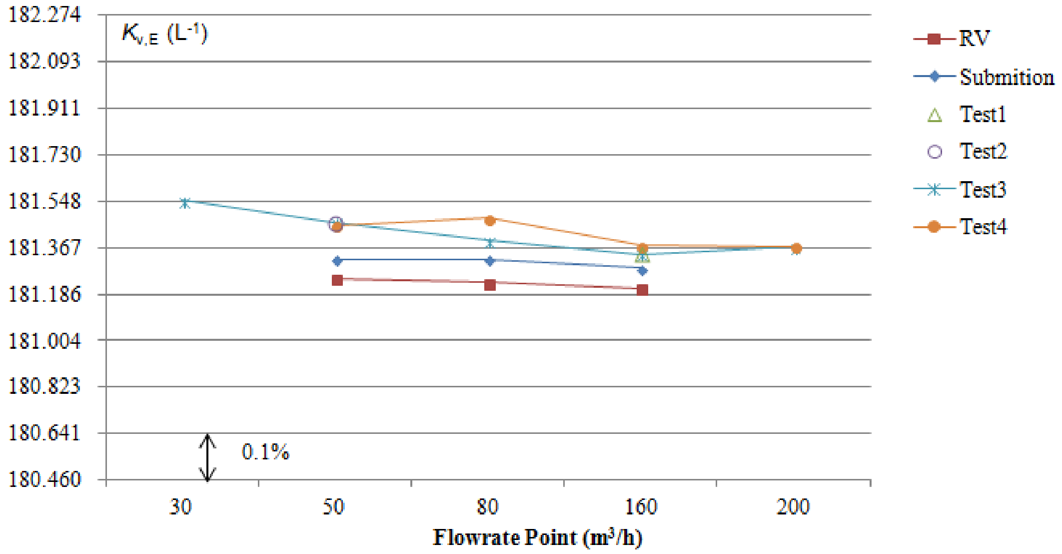


Figure 13 Summarization of data of the electromagnetic flowmeter at lab E

Lab E changed the water of their facility and the cleaned water tank after comparison. They tested TSP-1 again, and all experimental results of the turbine flowmeter entered into the equivalent domain.

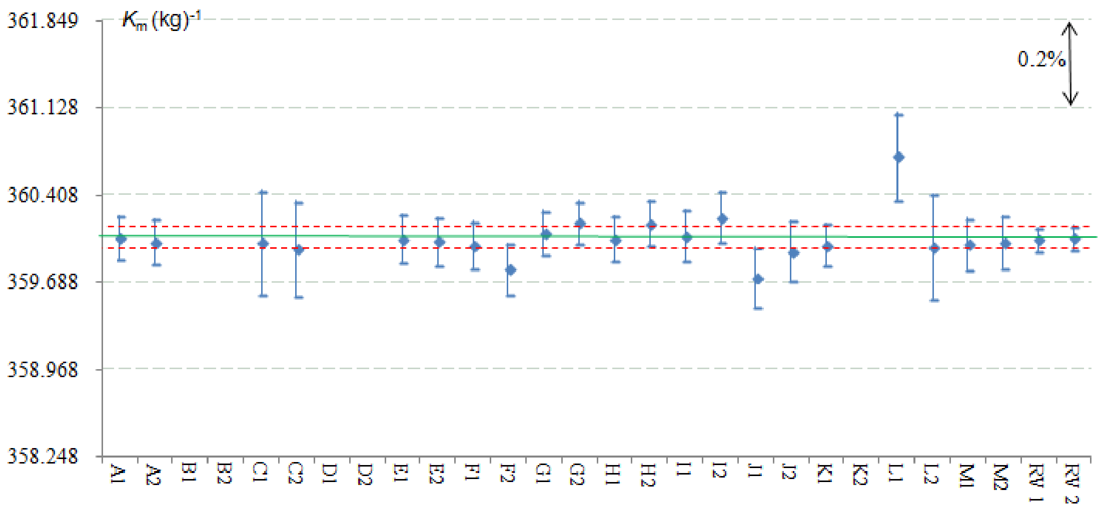
5.2 Comparison Result Analysis with TSP-2

Most participants completed the internal comparisons by using TSP-2. This comparison verifies the consistency of DN50 and DN100 test benches, but it also finds the error between two benches exceeds the acceptable range in certain labs. For example, lab L's results of internal comparison are shown in Table 7. E_n values at 30m^3/h are greater than 1, and E_n values at 20 m^3/h are close to 1. These comparison results are unsatisfactory for lab L.

Table 7 Lab L's Test results of TSP-2

Test Bench	30 m^3/h		20 m^3/h	
	K_m (kg^{-1})	U_r	K_m (kg^{-1})	U_r
DN50	359.984	0.12%	359.979	0.12%
DN100	360.730	0.10%	360.522	0.12%
Relative Deviation	-0.21%		-0.15%	
E_n	1.32		0.89	

Experimental results of TSP-2 on DN100 and DN50 test benches in all participating laboratories are compared horizontally (Figure 11, Figure 14). The experimental results of lab L on DN50 pipe are all within the equivalent domain. The results on DN100 pipe deviate significantly from the reference values at 3 flow rate. It can be known from the above analysis that problem exists at DN100 test bench more likely.



Note: Letters on the horizontal axis is the codes of laboratories; 1 denotes DN100 test bench; 2 denotes DN50 test bench.

Figure 14(a) Comparison results of TSP-2 (30m^3/h)

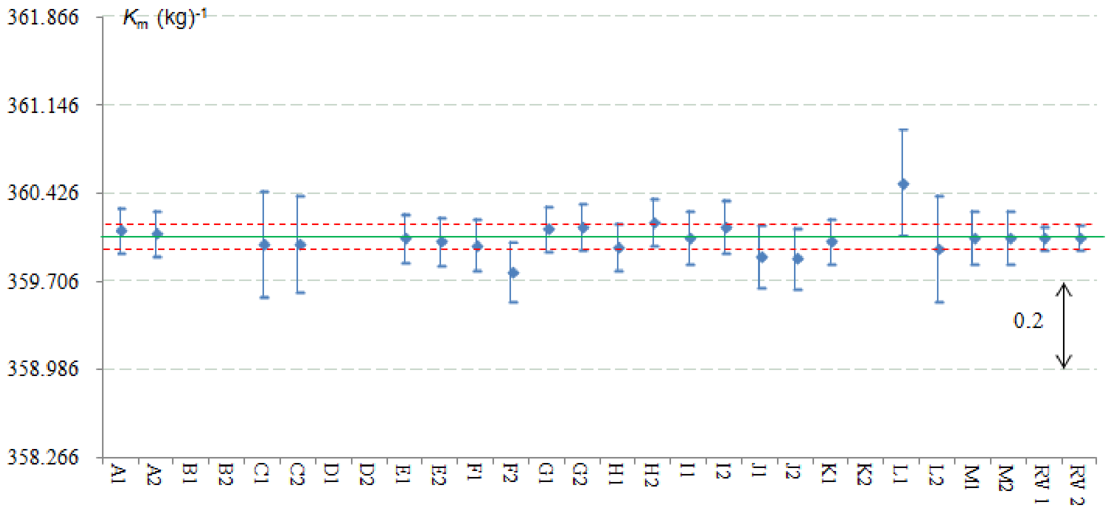


Figure 14(b) Comparison results of TSP-2 (20m^3/h)

It can be known from the original data that DN100 test bench uses the 1000L standard metal tank and diverter measurement system, but DN50 test bench uses 700L standard metal tank and diverter system (Note: the 1800L metal tank measurement system was used in experiment of TSP-1. Therefore, the results of TSP-1 are not included in this analysis). All data of lab L' and reference values are summarized in Figure 15. Using reference values as standard values, further analyses have revealed that an angle exists between the K-factor curves of experimental result and reference values for DN100 test bench.

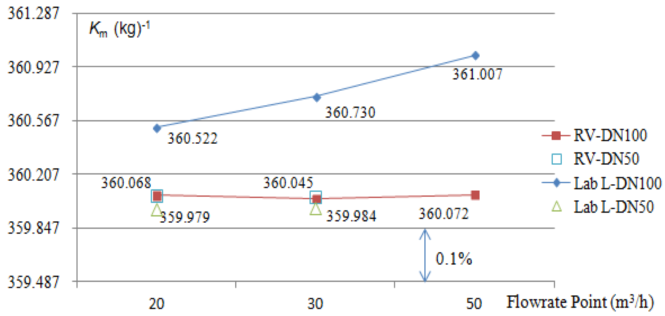


Figure 15 Summarization of data of TSP-2 at lab L

The facility of Lab L is a static volumetric method water flow facility, and the inflows into standard metal tank at each flow rate are roughly the same for the same test bench. If the measurements of standard tank are not accurate, the systematic errors of experimental results would be relatively fixed, and the two K-factor curves would be close to parallel. However, in Figure 15, the distance between the two curves increases as the flow increasing, which is to say that the deviation of DN100 test bench increases with the time (the time of water flowing into standard tank) decreasing. The positional deviation of synchronous trigger in the diverter system can cause this problem. In other words, the synchronous trigger position is not at the hydraulic center of nozzle. If the trigger point is advanced, the time of the pulse count will be longer than the actual measurement time by Δt, which will lead to a larger K-factor. With greater flow and higher frequency, the number of pulses counted within Δt will be higher, and the K-factor would also be larger. According to this analysis, the reasons for the problem should lie in the diverter of DN100 test bench.

After comparison, equipment aging is found in lab L. On DN100 test bench, some screws are loosened from the water separator, and positional deviation occurs. Thus, the judgment is verified. After maintenance of the diverter in lab L, the retested results are satisfactory.

6 Conclusions

Through the application of the two sets of TSP, national comparison of water flow has been successfully completed. Accepted by all participating laboratories, the results have already been announced publicly.

In designing the transfer standard, the situation of facilities and their different operating principles should be taken into account. The combination of velocity-type flowmeter TSP and mass flowmeter TSP can reflect the capacities and working conditions of facilities in a more objective and comprehensive manner. With fewer experiments, transfer standard by using combination of TSPs has obtained more information about the facilities. Such transfer standard provides the scientific bases and clues for the summarizing and analyzing of problems with water flow facilities. Both the series-connected flowmeters with different principles in TSP-1 and TSP-2 for internal comparisons are satisfaction in this comparison, and these designs can be applied to future comparison projects. They can also serve as the reference for the design of master meter or inspection standards of water flow facilities.

Acknowledgements

The authors gratefully acknowledge financial support from the National Science & Technology Pillar Program (No. 2009BAK66B01) and the National Public Benefit (Quality Inspection) Research Foundation (Grant no. 200910104).

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