Establishment of Air Flow Test Bench with Interact-Check Standards

Li Chuanjing, Chen Yunqi, Guo Aihua, Wang Jizhong, Yue Jian, Gu Shunfeng
Shanghai Institute of Process Automation Instrumentation
103 Cao Bao Road, Shanghai 200233, China
Tel: +86-21-64368180, Fax: +86-21-64333566, http://www.sipai.com
e-mail: lichuanjing@sipai.com

- **Abstract**

To enlarge the calibration capacity of existing air flow test bench in SIPAI with turbine master meters traced to bell prover, a newly-designed 4500 m^3/h flow test bench using critical nozzles as secondary standard traced to pVTt primary standard is successfully paralleled to the existing flow test bench for doubling the flow rate of original calibration capacity. It is proved that not only different secondary standards in kind, traced to both volumetric and gravimetric standards respectively, can be integrated to form an entire flow test bench, but the dependability of the test bench can be increased simply by interact-check principle instead of multi-laboratory inter-comparison test campaign. This flow test bench has been running for months, as a result a control chart of measurement uncertainty has been made. It shows the layout of this test bench is feasible and beneficial to improve the performance of the facility. Along with the running time goes by, an acceptable limitation between the divergent test results obtained from turbine and nozzle benches in accordance with regular interact-check procedure can be determined.

- **Keywords:** Uncertainty estimation, Interact check, Uncertainty control chart

- **Preface**

Founded in 1956, SIPAI, Shanghai Institute of Process Automation Instrumentation is a notified body authorized by the Government of PRC for evaluation of measuring instruments used in the field of process industries. In order to reinforce the capacity of natural gas meter calibration with the rapid development for use of natural gas in China, SIPAI purchased a complete set of negative pressure air flow calibration facility from Elster Messtechnik GmbH, Germany, ten years ago. The total flow rate is up to 4000 m^3/h and the secondary standards consist of three G1000/DN150 turbine meters for large flow and an 8-critical nozzle array for 1 to 255 m^3/h. In year 2008, SIPAI decided to extend the flow rate from 0.1 to 7500 m^3/h for the existing flow test bench, and also critical nozzles will be used as the secondary standard for the added part of flow test bench with negative pressure.

1. Configuration of newly-established air flow test bench

The basic configuration of the test bench is shown in figure 1. The nozzle arrays of SN1-4 and SN13-17 are newly added.
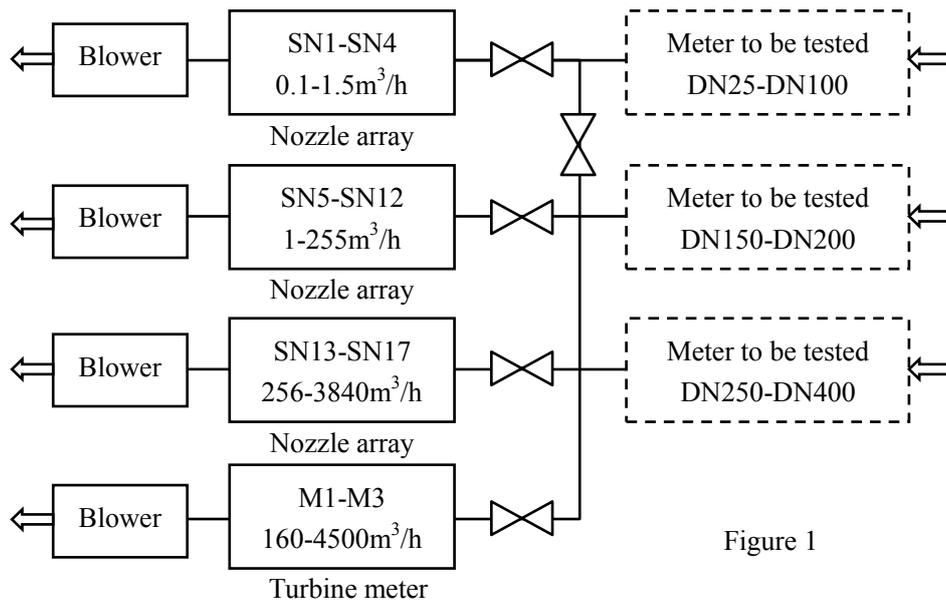
Figure 1

By means of careful arrangement for blowers and their connecting pipelines, the expected flow-rates are successfully paralleled for achieving approximately 7500 m^3/h. The figure 2 shows the nozzle array of SN1-4.
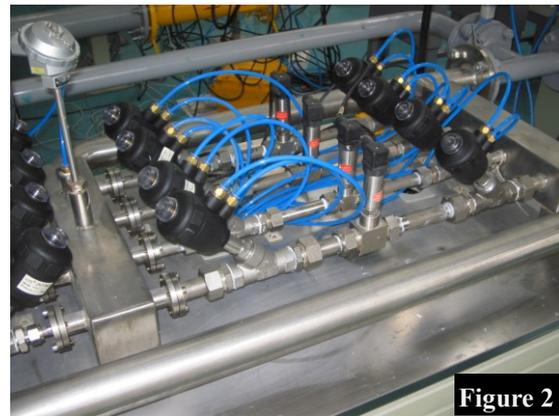

Figure 2

All blowers are well selected to reach the critical pressures which could be negative 30kPa especially for the smallest nozzles working on critical condition.

To ensure no leakage occurs on the pipeline that should be no flow in it through the nozzles, a leakage detection system is designed shown on figure 3. Two ON/OFF valves are installed in series along the pipeline downstream of the nozzle, and a pressure sensor is taking pressure between V1 and V2. In case that the leakage happens, that pressure cannot be retained, which indicates whether there is leakage happened.
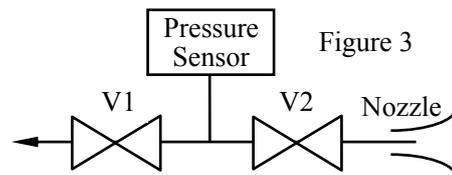

Figure 3

2. Traceability

As shown in figure 1, the test bench consists of two secondary standards, nozzles and master turbine meters, which traced to SIPAI's negative pressure PVTt primary standard and bell prover respectively. The primary standards are built up in 1980's by

SIPAI itself. The traceability chain is shown in figure 4. SIPAI's PVTt method facility was the first-built air flow standard in 1978 in China, and based on pure nitrogen replacement method and a precise balance with full scale of 100 kg and the resolution of 100 mg. The bell prover was also self-built with 10 m³ effective volume as the volumetric standard.
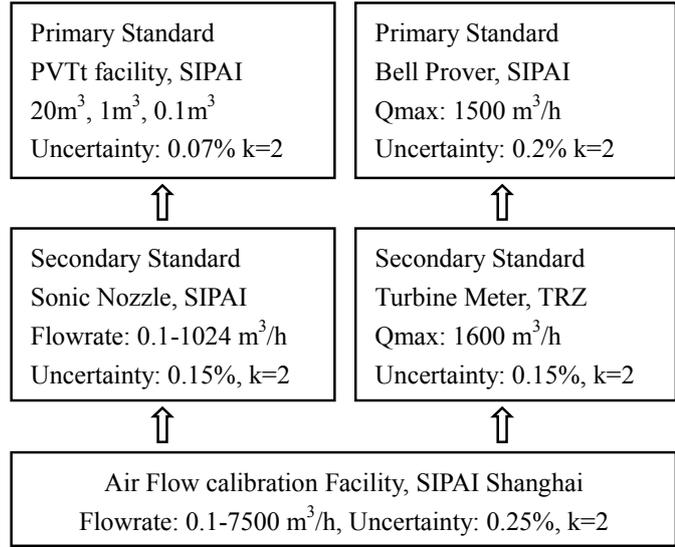
Primary Standard PVTt facility, SIPAI 20m³, 1m³, 0.1m³ Uncertainty: 0.07% k=2	Primary Standard Bell Prover, SIPAI Qmax: 1500 m³/h Uncertainty: 0.2% k=2
⇧	⇧
Secondary Standard Sonic Nozzle, SIPAI Flowrate: 0.1-1024 m³/h Uncertainty: 0.15%, k=2	Secondary Standard Turbine Meter, TRZ Qmax: 1600 m³/h Uncertainty: 0.15%, k=2
⇧	⇧
Air Flow calibration Facility, SIPAI Shanghai Flowrate: 0.1-7500 m³/h, Uncertainty: 0.25%, k=2	

Figure 4

3. Estimation of uncertainty

A. Uncertainty of nozzle's facility

Math model of nozzle's facility is shown below:

$$q_V = q_m \times \rho_m = A \times C \times C_* \times \frac{P_0 \sqrt{(R/M)} \times T_m \times Z_m}{\sqrt{T_0} \times p_m} \times 3600 \times k_{\phi 1}$$

Where, $\qquad \rho_m = \frac{p_m}{(R/M) \times T_m \times Z_m}$

q_V — Volumetric flow at meter to be tested in actual condition, m³/h
q_m — Mass flow at nozzle in actual condition, kg/h
A — Area of cross section at throat of nozzle, m²
C_* — Critical flow function of actual air, non-dimensional
C — Discharge coefficient of nozzle, non-dimensional
P_0 — Absolute stagnation air pressure at nozzle upstream, kPa
T_0 — Absolute stagnation air temperature at nozzle upstream, K
ρ_m — Air density at meter to be tested, kg/m³
P_m — Pressure at meter to be tested, kPa
T_m — Temperature at meter to be tested, K
Z_m — Air compressibility at meter to be tested
Φ — Air humidity, non-dimensional
P_H — Saturated vapor pressure, kPa
P — Standard atmosphere pressure, kPa
R — Gas constant of air, J·kmol·K⁻¹
M — Molar mass of air, kg·kmol⁻¹

Uncertainty estimation for nozzle's facility is described below. All inputs are listed in

following table (according to actual measurements).

Symbol	Source	Standard uncertainty of inputs $u_r(x_i)$ %	Index $p_i(x_i)$	$|p_i(x_i)|u_{rel}(x_i)$ %
$u_{rel}(C)$	Discharge coefficient	0.075	1	0.075
$u_{rel}(P_0)$	Stagnation pressure at nozzle upstream	0.029	1	0.029
$u_{rel}(T_0)$	Stagnation temperature at nozzle upstream	0.024	-0.5	0.012
$u_{rel}(T_m)$	Temperature at meter to be tested	0.024	1	0.024
$u_{rel}(P_m)$	Pressure at meter to be tested	0.029	-1	0.029
$u_{rel}(R)$	Molar mass	0.05	0.5	0.025

Above inputs are uncorrelated, and then:

$$u_{crel}^2 = \sum_{i=1}^{N} p_i^2 u_{rel}^2(x_i) = 0.0113 \times 10^{-4}, \qquad u_{crel} = 0.106\%$$

For mass flow, only No. 1, 2, 3, 6 inputs in above table are taken into account, then,

$$u_{crel} = 0.097\%$$

Calculation for extended uncertainties (k=2):

For volumetric flow, $U=0.106\% \times 2 = 0.21\%$
For mass flow, $U=0.097\% \times 2 = 0.19\%$

B. Uncertainty of turbine master meter facility

Math model of turbine master facility

$$q_V = \frac{p_w \times T_m}{T_w \times p_m} \times q_w$$

Where:
   q_V — Actual flow at meter to be tested, m³/h
   q_w — Volumetric flow at master meter, m³/h
   p_w — Pressure at master meter, Pa
   p_m — Pressure at meter to be tested, Pa
   T_w — Temperature at master meter, K
   T_m — Temperature at meter to be tested, K

Uncertainty estimation for master turbine's facility is described below. All inputs are listed in following table (according to actual measurements).

Symbol	Source	Standard uncertainty of inputs $u_r(x_i)$ %	Index $p_i(x_i)$	$|p_i(x_i)|u_{rel}(x_i)$ %
$u_{rel}(P_w)$	Pressure at master meter	0.029	1	0.029
$u_{rel}(T_w)$	Temperature at master meter	0.024	-1	0.024
$u_{rel}(T_m)$	Temperature at meter to be tested	0.024	1	0.024
$u_{rel}(P_m)$	Pressure at meter to be tested	0.029	-1	0.029
$u_s(qv)$	Uncertainty of bell prover	0.1	1	0.1
U_x	Repeatability of master meter	0.03	1	0.03

Above inputs are uncorrelated, and then:

$$u_{crel}^2 = \sum_{i=1}^{N} p_i^2 u_{rel}^2(x_i) = 0.012\% \times 10^{-4}, \qquad u_{crel} = 0.11\%$$

Calculation for extended uncertainties (k=2):

For volumetric flow, $U = 0.11\% \times 2 = 0.22\%$

4. **Uncertainty control charts**

To authorize the newly-built facility as a standard in one of the State notified bodies, SIPAI, in China, the uncertainty control chart shall be established by means of the way described as follows; i.e. a G1000/DN150 turbine meter is calibrated at certain flow rates, e.g. 1024 m³/h, with master turbine meter and critical nozzles respectively. The meter factor X and its range R can be obtained shown below. R=X$_{max}$−X$_{min}$.

No. for check	Master turbine as standard		Nozzle as standard	
	$\overline{X}$	R	$\overline{X}$	R
1	5359.2385	3.8932	5358.7606	1.6167
2	5358.1876	1.6722	5357.6183	0.4522
3	5359.2069	1.6297	5359.9420	0.6231
4	5359.2152	2.8101	5359.6268	2.0650
5	5362.2189	0.8504	5358.4190	0.8735

6	5364.0712	0.9849	5357.6125	0.4555
7	5363.0696	1.3565	5358.3591	2.5631
8	5363.0772	3.4897	5356.2519	2.5880
9	5359.8928	1.8757	5362.9579	0.3956
10	5358.2201	2.1305	5363.4722	1.8366
	$\bar{X}_{av}$=5360.6398	$\bar{R}$=2.0693	$\bar{X}_{av}$=5359.3020	$\bar{R}$=1.3469

As the times of checking n=10, and the time interval of checking is about two weeks, also the tests at 1024 m^3/h for one checking are repeated for six times. In this condition, range method should be adopted. Then, the CL (central line), UCL (upper control line) and LCL (lower control line) can be calculated.

For master **turbine's** tests, $\bar{X}$ chart:
$$CL = \bar{X}_{av} = 5360.6398$$
$$UCL = \bar{X}_{av} + A_2\bar{R} = 5360.6398 + 0.308 \times 2.0693 = 5361.277$$
$$LCL = \bar{X}_{av} - A_2\bar{R} = 5360.6398 - 0.308 \times 2.0693 = 5360.002$$

For master **turbine's** tests, R chart:
$$CL = \bar{R} = 2.0693$$
$$UCL = D_4\bar{R} = 1.777 \times 2.0693 = 3.677$$

For **nozzle's** tests, $\bar{X}$ chart:
$$CL = \bar{X}_{av} = 5359.3020$$
$$UCL = \bar{X}_{av} + A_2\bar{R} = 5359.3020 + 0.308 \times 1.3469 = 5359.717$$
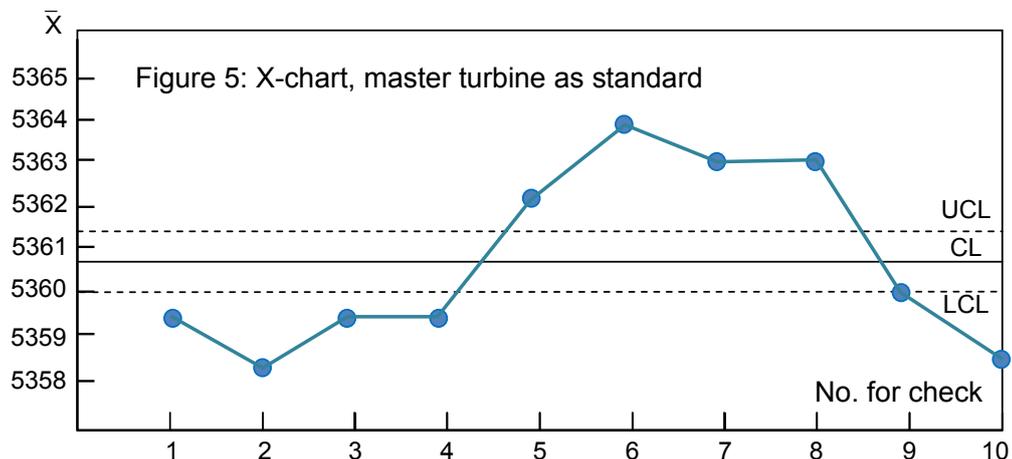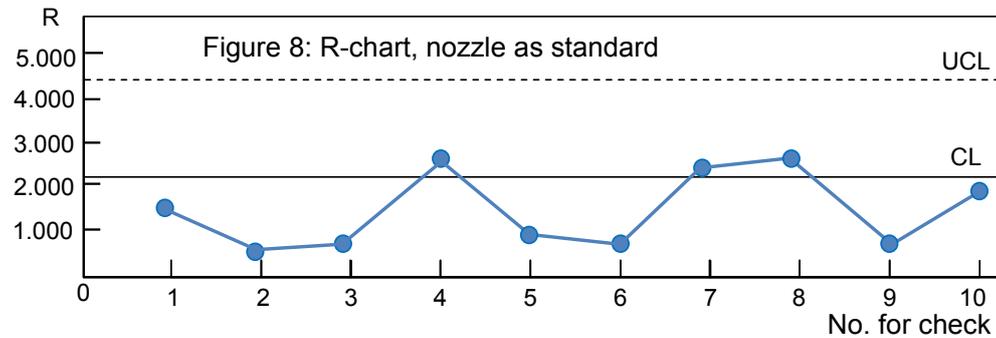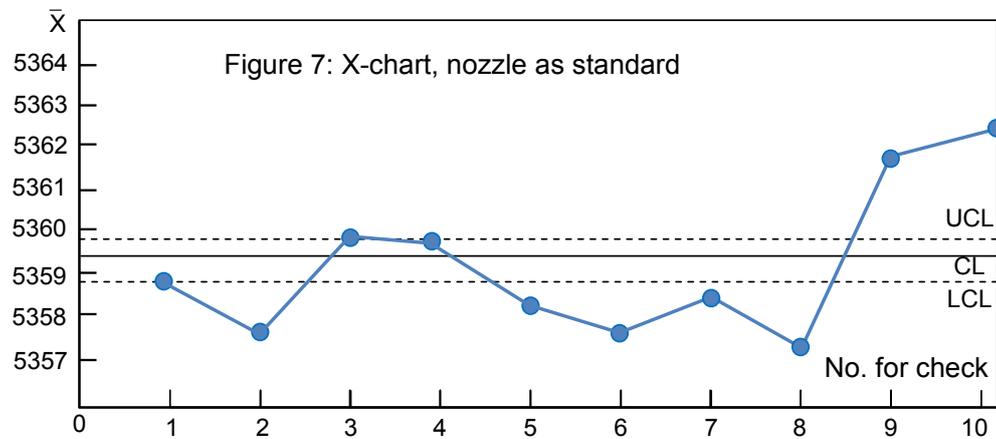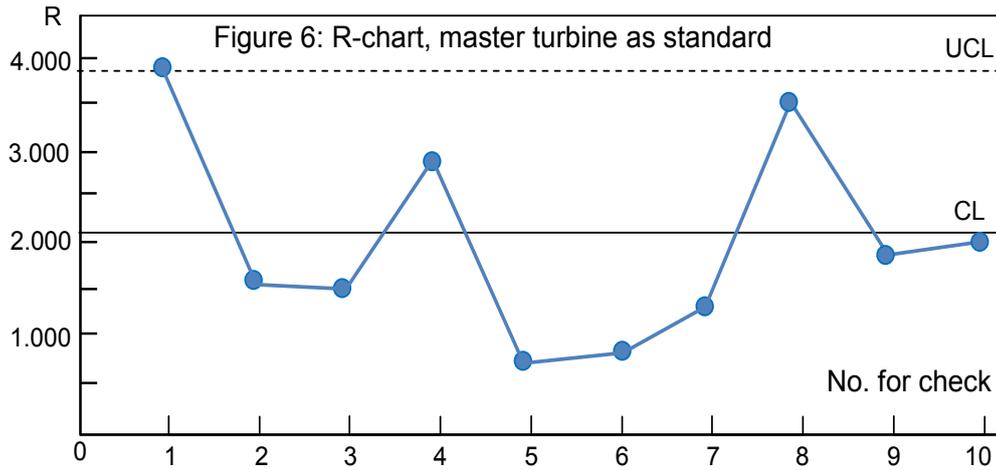$$LCL = \bar{X}_{av} - A_2\bar{R} = 5359.3020 - 0.308 \times 1.3469 = 5358.887$$

For **nozzle's** tests, R chart:
$$CL = \bar{R} = 1.3469$$
$$UCL = D_4\bar{R} = 1.777 \times 1.3469 = 2.393$$

Where, A_2, D_3, D_4 are the factors for $\bar{X}$-R chart which can be found in reference paper No. 1. In terms of above data, the uncertainty control charts can be made.

Figure 5: X-chart, master turbine as standard

Figure 6: R-chart, master turbine as standard

Figure 7: X-chart, nozzle as standard

Figure 8: R-chart, nozzle as standard

5. Interact-check standards

Statistical tests may be used to determine whether the tests from these two methods, with master turbine and nozzle as transfer standards, are different. These tests can be treated as the samples from two populations. The goal is to test whether the means of the two populations are equal. If two populations are assumed to be independently normally distributed, t-test can be conducted. If the distributions of the two populations cannot be easily determined, a nonparametric statistical test named Wilcoxon signed-rank test can be used. Both tests can examine whether the means of two populations are statistically significantly equal, given a certain significance level;

furthermore, they can measure how different the two means are by looking at the P-values of the tests. In this case, if the sample size is large enough, the tests can be assumed to be normal distributed, so t-test would be appropriate. Anyway, one can judge whether the test results from the facility can be accepted by statistical method instead of analysis of uncertainty control chart only.

6. Discussion

A. Since the establishment of this facility was accomplished just a few months ago, system commissioning is being carried out nowadays, which causes that the preliminary tests cannot be well-processed, and some of the test results are not as correct as they should be. Figure 7 shows that the test results are scattered, which indicates that gross errors might occur. The further system commissioning should be done in the future.

B. In despite of that the uncertainty control charts are made, it is obvious that the tests are not enough to reflect the long term stabilities for the facility and meter behaviors. And also, the time interval is not long enough to explore the changing of facility and meter performance.

C. The availability of interact check by a reference meter is evidenced by means of exploring the deviation between the meter factors obtained from different traceability chains. The test results of meter factors shown above are not accepted, meaning system commissioning shouldn't be ended off until the meter factors are approached evidently. In order to follow up with the confidence level estimation for the facility, statistical method is recommended to simplify the inter-comparison test in the future.

7. Acknowledgement

▪ **References**

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