Traceable Calibrations from Primary Standard to On-Site Ultrasonic Flowmeter

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Abstract: This paper describes the traceable calibrations from primary standard to on-site natural gas ultrasonic flowmeters. In practice, the National Metrology Laboratory constructed a gravimetric type air-flow calibration system with sonic nozzle array as the working standard in 1993. The flow measurement capacity of this primary standard at 1 bar and 20 ℃ is from 15 m^3/h to 18000 m^3/h with operating pressure range from 1 bar to 60 bars. A re-circulating high pressure gas flow measurement facility was constructed at Chinese Petroleum Corp in southern part of Taiwan. The pressure range is also from 1 bar to 60 bars with flow range from 20 m^3/h to 4000 m^3/h under actual pressure condition. The transfer standards of this re-circulating facility are four 6" Instromet ultrasonic flowmeters. The expanded uncertainty of these four transfer standards calibrated by NML compact nozzles was 0.18 %. For the Da-Tan distribution and metering station in Taiwan, four Sick 12" ultrasonic flowmeters are used as transfer standards. These were calibrated by the re-circulating facility regularly and expanded uncertainty for the transfer standard was 0.24 %. Subsequently, six on-site Daniel 24" ultrasonic flowmeters are calibrated by transfer standards with the expanded uncertainty of 0.26 %. The pressure effect of the ultrasonic flowmeter was tested and proved insigificant. The calibration curve of ultrasonic flowmeter at specific pressure can be used at any pressure.

Keywords: Traceabe calibration, Ultrasonic flowmeter, Uncertainty analysis

1. Introduction

The deterioration of air quality and environmental pollution caused by energy consumption are getting worse all over the world. To implement energy diversification policies of the Taiwan government, Taiwan Power Company adopted natural gas as the fuel of Da-Tan thermal power plant aiming at reducing carbon emission. The yearly power output of Da-Tan thermal power plant is 13,245 million kiloWatt-hour. In its operation, the metering accuracy of the natural gas is very important for fair trade between Taiwan Power Company and Chinese Petroleum Corporation. If a metering error of natural gas consumption goes up by 1 %, the difference in custody transfer in natural gas exceeds 2 million USD yearly. Thus, contract between both companies specifies calibration and traceability of Da-Tan metering facilities be audited by a domestic, independent organization, that has experience in high pressure gas flow calibration. Starting 2010, the Center for Measurement Standards/ITRI is entrusted with such responsibility to govern this legal metrology infrastructure in Taiwan. This paper describes the traceable calibration from primary standard to on-site natural gas ultrasonic flowmeters.

The metering flowmeters of Da-Tan metering facilities were 24” Daniel ultrasonic flowmeters which accuracy approved by the 12” Sick ultrasonic flowmeters at Da-Tan metering station. These 12” Sick ultrasonic flowmeters were calibrated by the 6” Instromet ultrasonic flowmeters of the secondary standard. The 6” Instromet ultrasonic flowmeters were traceable calibrated by the compact nozzle of the primary standard which belongs to National Metrology Laboratory of Taiwan. At each calibration step the ultrasonic flowmeters were used. These ultrasonic flowmeters use measurements of the transit time of high frequency pulses between four pairs of transducers to determine the volumetric flow rate in the meter. Comparing the other type flowmeters, the ultrasonic flowmeter own some advantages such as self-diagnosis, no moving parts, structure simply, maintenance easily and low maintenance cost. The use of ultrasonic flowmeters for custody transfer has grown substantially over the past ten years[1]. In the field of natural gas, ultrasonic flowmeters seem to provide satisfying results both for small and large flows.

The turbine flowmeter plays a role of custody transfer also in the commerce of natural gas. The calibrating errors of a turbine flowmeter show an error curve of depending on the flowrate. There is different error curve when a turbine flowmeter operates at different pressure. The using of error curve of a turbine flowmeter has to carefully. From many message sources, the change of error curve of an ultrasonic flowmeter is not noticeable when the operating pressure changes. By the way, the error curve is independent of the medium gas also. These are the potential advantages of an ultrasonic flowmeter.

2. Primary and Secondary Calibration System

A primary high pressure air flow measurement standard was constructed in Taiwan with a capacity of 18,000 m^3/h and pressure range of 1~60 bar[2]. The schematic diagram is shown in figure 1. It is a blow-down type facility with a gyroscopic weighing scale suitable for high precision gravimetric measurements. The maximum advantage of the blow-down type facility is the ability to endure greater pressure difference due to piping and flowmeter(ex. Sonic nozzle). The gyroscopic weighing scale, made by Wohwa in Germany, has a measurement capacity of 160 kg with a 2 grams resolution. The measurement uncertainty of the gyroscopic scale was estimated to be 0.013 % at a collecting weight of 20 kg. A gyroscopic weighing scale and a fast acting diverter and a sliding-joint mechanism were utilized to perform primary mass flow calibration. The diverter of the system plays an important role in making an accurate calibration of a sonic nozzle. The rack and pinion device and the two 90 degree out-of-phase ball valves were designed to have a switching over time of less than 60 ms via the control of a hydraulic actuator. The collecting time of the compressed air in the weight tank is measured by a timer triggering position has to be carefully adjusted so that the timer starts and stops at about the mid-point during the valve opening and closing sessions. Otherwise, in a high flowrate situation, because the collecting time is limited by the choke condition of the nozzle, excessive timing error will cause the discharge coefficient to be over- or under-estimated. A compact nozzle array, which incorporates seven sonic nozzles with different throat diameters in a large plenum, is the reference standard meters and provides for flexibility in mass flow control.

The through-flow and re-circulating loop system were used frequently as the design concepts of the secondary flow facility. Through-flow system is a simple and straightforward calibration method in which gas is fed to and withdrawn from the system continually during operation. There are, clearly, various ways in which the gas removed from a through-flow system can be handled including recompression, buffer storage volume and liquefaction. At high flow rates significant volumes of gas would require storage, recompression or liquefaction and need extra cost for handling it. This is the disadvantage of the through-flow system. The re-circulating loop system is in the form of a closed loop charged with gas to the required pressure and held at this pressure. Flow is induced through the loop by a blower and, as long as there are no restriction on the blower power supply, the flow can be continuous and so it should be possible to achieve extremely stable condition. The case with which pressure can be altered at will, the wide range of flow rates possible from inverter and bypass line as well as the ability to run continuously clearly demonstrate the potential of a re-circulating system as a research tool.

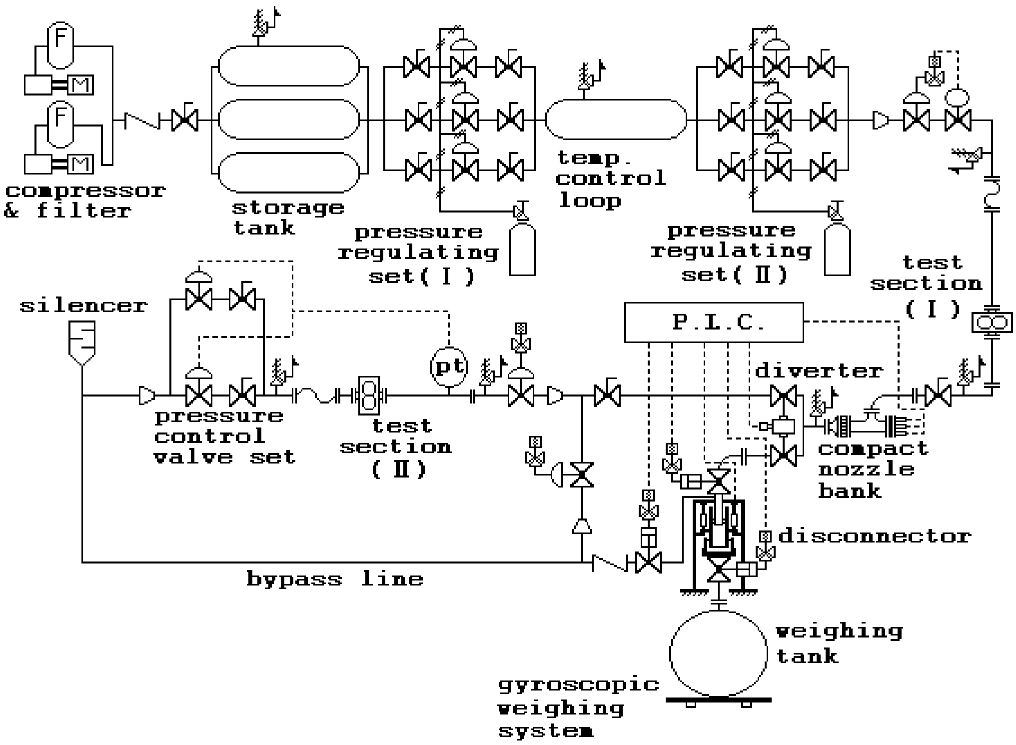

Fig. 1 Primary high pressure air flow measurement standard

A re-circulating high pressure gas flow measurement facility was commissioned in Chinese Petroleum Corporation with the maximum flow rates of 4000 m^3/h and pressure range up to 60 bar[3]. The schematic diagram is shown in figure 2. The re-circulating loop consists of three high pressure encapsulated blowers, a cooling system, a piping system, and a GE Fanuc Programming Logic Controller(PLC) based data acquisition module. The capacity of these three blowers one is 600 m^3/h, and the other two are 1700 m^3/h when the working pressure is 60 bar with 4.5 bar pressure difference. The amount of heat generated by the blower is proportional to the mass flow rate and need to be removed from the flow stream by a heat exchanger. A shell-and-tube type heat exchanger is located on the immediately downstream of the blower to reduce the heat generated by the blower. It is designed to maintain the temperature stability of the gas flow to within ±0.5℃ when the gas flow rate is up to 4000 m^3/h. The mass flow rate of the re-circulating system is from 0.00645 kg/s to 77.429 kg/s, about 1 to 12000 turndown ratio.

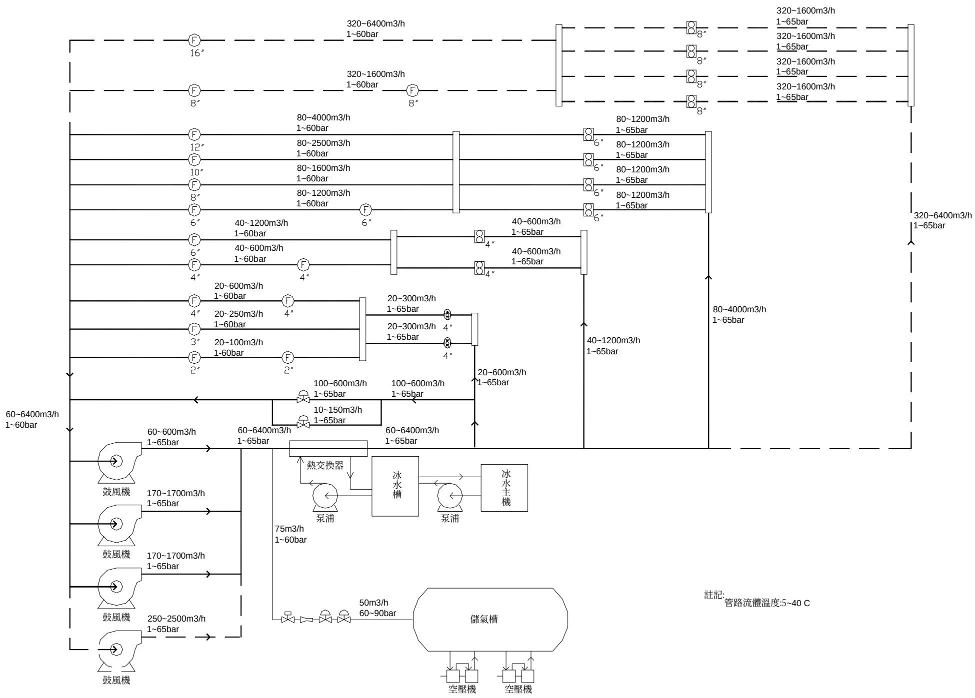

Fig. 2 Re-circulating high pressure gas flow measurement facility

3. Uncertainty Analysis

The uncertainty evaluation of the on-site 24” Daniel ultrasonic flowmeters were introduced as follows. Table 1 lists the steps of the traceable calibration of this on-site ultrasonic flowmeters.

Table. 1 Steps of the traceable calibration of on-site 24” Daniel ultrasonic flowmeters

Step	Standard Flowmeter	Meter under test	Calibration facility
1	Compact nozzles	Four 6” Instromet ultrasonic flowmeters	Primary standard
2	Four 6” Instromet ultrasonic flowmeters	Four 12” Sick ultrasonic flowmeters	Secondary standard
3	Four 12” Sick ultrasonic flowmeters	Six 24” Daniel ultrasonic flowmeters	Da-Tan metering facility

From mass conservation law, the total mass through the standard flowmeters equal to the total mass through the testing flowmeter.

$$m_t = \sum_{i=1}^{n} m_i \Rightarrow V_t \frac{P_t}{Z_t R T_t} = \sum_{i=1}^{n} V_i \frac{P_i}{Z_i R T_i} \quad (1)$$

where

m : Mass of the gas

V : Volume of the gas

P : Absolute pressure

T : Absolute temperature

Z : Compressibility

R : Gas constant

t : index of the meter under test

i : index of the standard flowmeter

Arranging formula (1) and supposing the performance of the standard flowmeters, the pressure gages and thermometers were the same, we can write

$$\frac{dV_t}{V_t} \approx \frac{dP_i}{P_i} - \frac{dP_t}{P_t} + \frac{dT_t}{T_t} - \frac{dT_i}{T_i} + \frac{dZ_t}{Z_t} - \frac{dZ_i}{Z_i} + \frac{dV_i}{V_i} \tag{2}$$

Since the pressure and temperature variations of the standard flowmeter and under test flowmeter have the same trend, we can consider the pressure and the temperature variations of these two flowmeters to be the variation of the pressure difference and temperature difference between these two flowmeters. That is

$$\frac{dP_i}{P_i} - \frac{dP_t}{P_t} \approx \frac{d\left(P_i - P_t\right)}{P_i} \tag{3}$$

Supposing u_1 is the standard deviation of the traceability, u_2 is the standard deviation of the measurement. P_i, P_t trace to the same standard source, then $u_1(P_i)$ and $u_1(P_t)$ are canceled each other. Similarly, $u_1(T_i)$ and $u_1(T_t)$ are canceled each other too.

$$Z = Z\left(P,T\right) \Rightarrow \frac{dZ}{Z} = \frac{P}{Z}\frac{\partial Z}{\partial P}\frac{dP}{P} + \frac{T}{Z}\frac{\partial Z}{\partial T}\frac{dT}{T} \tag{4}$$

Substituting equation (4) into equation (2), we have

$$\frac{dV_t}{V_t} \approx \left(1 - \frac{P_i}{Z_i}\frac{\partial Z_i}{\partial P_i}\right)\frac{d\left(P_i - P_t\right)}{P_i} + \left(1 + \frac{T_i}{Z_i}\frac{\partial Z_i}{\partial T_i}\right)\frac{d\left(T_t - T_i\right)}{T_i} + \frac{dV_i}{V_i} \tag{5}$$

The working fluid of the secondary standard is the air, so

At 60 bara, 20 ℃

$$\frac{P}{Z}\frac{\partial Z}{\partial P} \approx -4.3\times10^{-3}, \frac{T}{Z}\frac{\partial Z}{\partial T} \approx 0.15$$

At 1 bara, 20 ℃

$$\frac{P}{Z}\frac{\partial Z}{\partial P} \approx -4\times10^{-4}, \frac{T}{Z}\frac{\partial Z}{\partial T} \approx 2.6\times10^{-3}$$

The working fluid of the Da-Tan metering station is the natural gas, so

At 60 bara, 15 ℃

$$\frac{P}{Z}\frac{\partial Z}{\partial P} \approx -0.136, \frac{T}{Z}\frac{\partial Z}{\partial T} \approx 0.592$$

At 1 bara, 15 ℃

$$\frac{P}{Z}\frac{\partial Z}{\partial P} \approx -2\times10^{-3}, \frac{T}{Z}\frac{\partial Z}{\partial T} \approx 8\times10^{-3}$$

The larger value of above equations was chosen to substitute into equation (5). Equation (5) is expressed in standard uncertainty form.

$$\left(\frac{u(V_t)}{V_t}\right)^2 = \left(1-\frac{P_i}{Z_i}\frac{\partial Z_i}{\partial P_i}\right)^2\left(\frac{u_2(P_i-P_t)}{P_i}\right)^2 + \left(1+\frac{T_i}{Z_i}\frac{\partial Z_i}{\partial T_i}\right)^2\left(\frac{u_2(T_i-T_t)}{T_i}\right)^2 + \left(\frac{u(V_i)}{V_i}\right)^2 \quad (6)$$

The maximum standard deviation of the pressure difference and temperature difference of the secondary standard were 0.026 % and 0.049 %[2]. The maximum standard deviation of the pressure difference and temperature difference of the Da-Tan metering facility were 0.017 % and 0.005 %. The expanded uncertainty evaluation of each step is listed at table 2.

Table. 2 The expanded uncertainty evaluation of each step

Step	Item of relative uncertainty	Manufactory specification	Degree of freedom	Relative uncertainty	Note
1	$\frac{U(V_t)}{V_t}$	6" Instromet ultrasonic flowmeter	100	1.98╳0.09% =0.178%	0.09% is traceability uncertainty
2	$\frac{u_2(P_i-P_t)}{P_i}$	DHI RPM4 Priminum / 0.01% of reading	∞	0.026%	Maximum standard deviation of pressure difference from [3]
	$\frac{u_2(T_i-T_t)}{T_i}$	Four wire platinum resistance thermometer	∞	0.049%	Maximum standard deviation of temperature difference from [3]
	$\frac{u(V_i)}{V_i}$	6" Instromet ultrasonic flowmeter / reproducibility 0.05%	171	$\sqrt{0.09^2+0.05^2}\,\%$ $=0.103\%$	Traceability to primary standard
	$\frac{U(V_t)}{V_t}$	12" Sick ultrasonic flowmeter	318	0.237%	
3	$\frac{u_2(P_i-P_t)}{P_i}$	Rosemount 3051 S	∞	0.017%	From test data
	$\frac{u_2(T_i-T_t)}{T_i}$	Rosemount 3144 P/ four wire platinum resistance thermometer	∞	0.005%	From test data
	$\frac{u(V_i)}{V_i}$	12" Sick ultrasonic flowmeter / reproducibility 0.05%	438	$\sqrt{0.12^2+0.05^2}\,\%$ $=0.130\%$	Traceability to secondary standard
	$\frac{U(V_t)}{V_t}$	24" Daniel ultrasonic flowmeter	461	0.259%	

The four 6" Instromet ultrasonic flowmeters were calibrated by the compact nozzles of the primary standard with an expanded uncertainty of 0.178 %. The four 12" Sick ultrasonic flowmeters were calibrated by the secondary facility with an expanded uncertainty of 0.237 %. The 24" Daniel ultrasonic flowmeter were calibrated by 12" Sick ultrasonic flowmeter at Da-Tan metering station with the expanded uncertainty of 0.259 %.

4. Pressure Effect of Ultrasonic Flowmeter

Instromet 6" ultrasonic flowmeter was calibrated by the compact nozzle array at different pressure to study whether there were different errors. The flowrate of the compact nozzle array was kept 200 m^3/h and the pressures were controlled at 15 bar, 35 bar and 50 bar. Figure 3 shows the calibration results. The distribution of calibrating data was inside ±0.2 % of average. The results suggest that the pressure effect of the ultrasonic flowmeter was insignificant.

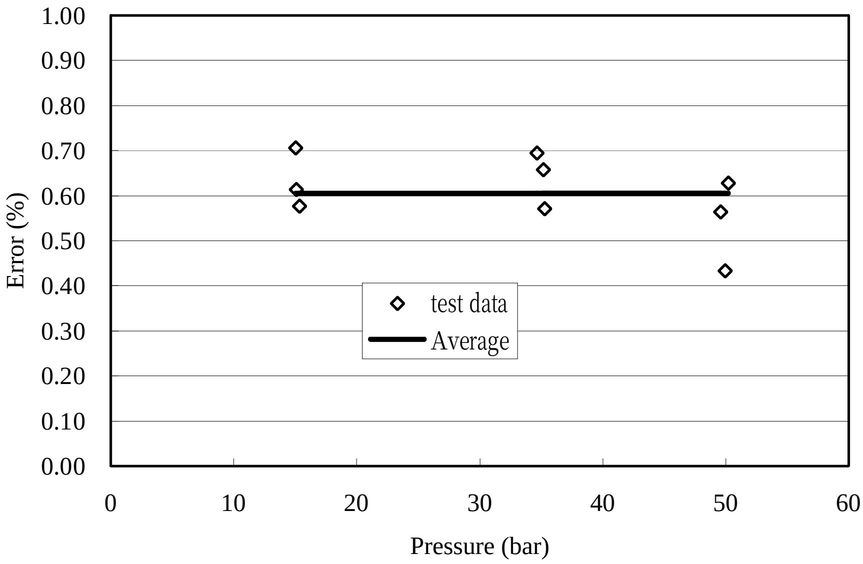

Fig. 3 Errors distribution of ultrasonic flowmeter to be calibrated by the compact nozzle array

5. Conclusion

There were three steps for traceable calibration of 24" ultrasonic flowmeter of Da-Tan metering station in Taiwan. First step, using sonic nozzles of national standard to calibrate the 6" ultrasonic flowmeters with an expanded uncertainty of 0.18 %. Second step, using 6" ultrasonic flowmeters to calibrate 12" ultrasonic flowmeters with an expanded uncertainty of 0.24 %. The last step, 24" ultrasonic flowmeters were calibrated by 12" ultrasonic flowmeters and the expanded uncertainty of each 24" flowmeter was 0.26 %. Independent tests showed that there was not pressure effect for the Instromet 6" ultrasonic flowmeter. The calibrating curve of ultrasonic flowmeter at specific pressure can be used at any pressure.

Acknowledgment

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